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	Engineering and Design ICE ENGINEERING	
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CECW-EH

DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, DC 20314-1000

EM 1110-2-1612

Manual
No. 1110-2-1612

30 April 1999

Engineering and Design
ICE ENGINEERING

1. Purpose. This manual, composed of three parts, presents in Part I the current guidance for the planning, design, construction, and operation and maintenance of ice control and ice suppression measures for Corps of Engineers projects; provides in Part II the current guidance for dealing with ice jams and the resultant flooding, including preventive measures; and gives in Part III the current guidance for engineering and operational solutions to ice problems on rivers used for navigation.

2. Applicability. This manual is applicable to all USACE commands having responsibility for civil works design, construction, operations, and maintenance.

3. Discussion. All Corps projects subjected to freezing temperatures have ice problems, such as: ice buildup on lock walls, hydropower intakes, and lock approaches; ice accumulation in navigation channels; ice passage over spillways that scours the downstream channels; and ice damage to shore structures and shorelines, etc. Therefore, ice control measures should be considered for both new and existing projects to improve operations and safety in cold regions. In Part I this manual discusses ice formation processes, physical properties, and potential solutions to associated problems. Part II considers the problem of ice jams and ice jam flooding, and discusses a broad range of mitigation measures. Part III of this manual addresses the considerations that arise from winter navigation on inland waterways, including the conduct of river ice management studies and the preparation of river ice management plans.

4. Distribution statement. Approved for public release, distribution is unlimited.

FOR THE COMMANDER:

ALBERT J. GENETTI, JR.
Major General, USA
Chief of Staff

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Table of Contents

Chapter 1
Introduction

1-1. Purpose

This manual provides a general coverage of the field of ice engineering as it pertains to the responsibilities of the Corps of Engineers. For convenience, it is divided into three parts: first, *Ice Properties, Processes, and Problem Solutions*; second, *Ice Jams and Mitigation Measures*; and third, *Winter Navigation on Inland Waterways*. This manual does not address the environmental impacts of ice.

a. Role.

(1) Part I gives fundamental information about ice and about the hydraulics of ice-affected river flow. It presents current guidance for the planning, design, construction, and operation and maintenance of ice-control and ice-suppression measures for Corps of Engineers projects. It also supplies basic information on selected problems for which ice is a significant engineering factor.

(2) Part II addresses ice jams and related flooding, including prevention and remediation methods. The information presented is intended to be useful to interested parties outside of the Corps of Engineers, as well as within.

(3) Part III gives the current guidance for engineering and operational solutions to ice problems on rivers used for navigation throughout the winter. These solutions can contribute to efficient, cost-effective, reliable, and safe navigation during ice periods. Part III also presents guidance for developing River Ice Management Plans for specific rivers or river systems.

b. Scope.

(1) In Part I, *Ice Properties, Processes, and Problem Solutions*, Chapter 2 discusses ice processes, namely formation, growth, and decay, and the physical and mechanical properties of ice. In Chapter 3 the focus is on techniques for mechanical and thermal ice control in lakes and rivers. Chapter 4 describes methods for modeling the hydraulics of ice-affected rivers and determining the associated water-surface profiles, while Chapter 5 presents approaches for assessing ice-affected stage-frequencies for rivers. Chapter 6 discusses ice-induced forces on riverine, coastal, and offshore structures for inclusion in design considerations. Chapter 7 presents guidance on estimating the effects of ice covers on sediment transport in alluvial channels. Chapter 8 deals with evaluating the bearing capacity of sheet ice for stationary and moving loads as a function of ice thickness and ice conditions. Chapter 9 discusses small-scale ice physical modeling that can be conducted to test concepts for resolving ice problems in all types of water bodies.

(2) In Part II, *Ice Jams and Mitigation Measures*, Chapter 10 presents a general overview of the problem of ice jams and ice jam flooding. Chapter 11 gives a brief review of ice types as a basis for discussing the types of ice jams, their causes, and their prediction. Chapter 12 covers the broad range of methods used to reduce or eliminate ice jam difficulties.

(3) In Part III, *Winter Navigation on Inland Waterways*, Chapter 13 discusses the conduct of a river ice management study, a system-wide approach to solving winter navigation problems. In Chapter 14 the broad range of river ice problems affecting winter navigation is summarized, and guidance for identifying

and conducting surveys of these problems is given. Chapter 15 presents river ice forecasting concepts and methodologies. Systems and techniques for the collection of hydrometeorological data are covered in Chapter 16, including numerical information as well as imagery. Chapter 17 presents basic information regarding navigation in ice, and includes discussion of alternatives for increasing the ease and efficiency of such operations. Chapter 18 addresses structural solutions to ice problems at navigation structures. Lastly, Chapter 19 covers operational solutions to winter navigation problems.

(4) Appendix A, *Glossary*, provides abbreviations and definitions of terms used throughout this manual. Appendix B, *Ice Jam Mitigation Case Studies*, is related to Part II and provides details for many solutions successfully applied to a wide variety of ice jam problems. Appendix C, *Typical River Ice Management Study*, associated with Part III, outlines and organizes the elements necessary to a river ice management study, which would lead to a formal River Ice Management Plan.

1-2. Applicability

This manual is applicable to all USACE commands having civil works design, construction, or operations responsibilities.

1-3. Explanations of Terms

Abbreviations and special terms used in this manual are listed in Appendix A, *Glossary*.

1-4. Ice Impacts on Corps Activities

Figure 1-1 shows the area of North America where temperatures in winter are below freezing over a sufficient length of time for ice to form in rivers, streams, and lakes. Ice in streams and waterways affects Corps projects for navigation, flood control, water supply, and power generation. It can also result in ice jams and lead to flooding at river discharges that would be trouble-free under open-water conditions. During spring breakup, especially, ice may severely damage riprap installations and other riverine structures. Offshore and coastal structures in the Arctic and in subarctic regions, and specifically along the Alaska coastline, need to be designed to withstand the significant forces exerted by sea ice driven by wind or current. Ice in navigable waterways adversely affects many Corps activities and creates the need for specific ice management measures.

a. Ice interference with lock and dam operations. Corps of Engineers navigation projects cannot operate properly when ice accumulates at locks, dams, and related facilities. A few examples illustrate how ice at navigation projects leads to accelerated damage and increased maintenance needs, greater demands on personnel, and more dangerous working conditions. Ice interferes with the movement of lock and dam gates (Figure 1-2) and places added loads on structural components. Lock widths are often not fully usable owing to the accumulation of broken ice in recesses behind miter gates (preventing full gate opening) and the buildup of ice collars on one or both walls of the chamber (Figure 1-3). Broken ice is pushed into lock chambers ahead of tows, sometimes limiting the length of tow that can fit. Floating mooring bitts freeze in place, becoming useless. The passing of ice at dams, while simultaneously trying to maintain navigation pool levels and avoid downstream scour, is often difficult or impossible.

b. Ice effects at flood control projects. Problems at flood control projects are often similar to those at navigation facilities. Dam gates are particularly susceptible to freezing in place because of leaking seals and resulting ice buildup, especially if gates are moved infrequently. Hoisting chains, trunnion arms, etc., may become so loaded with ice as to be too heavy for lifting mechanisms. Personnel

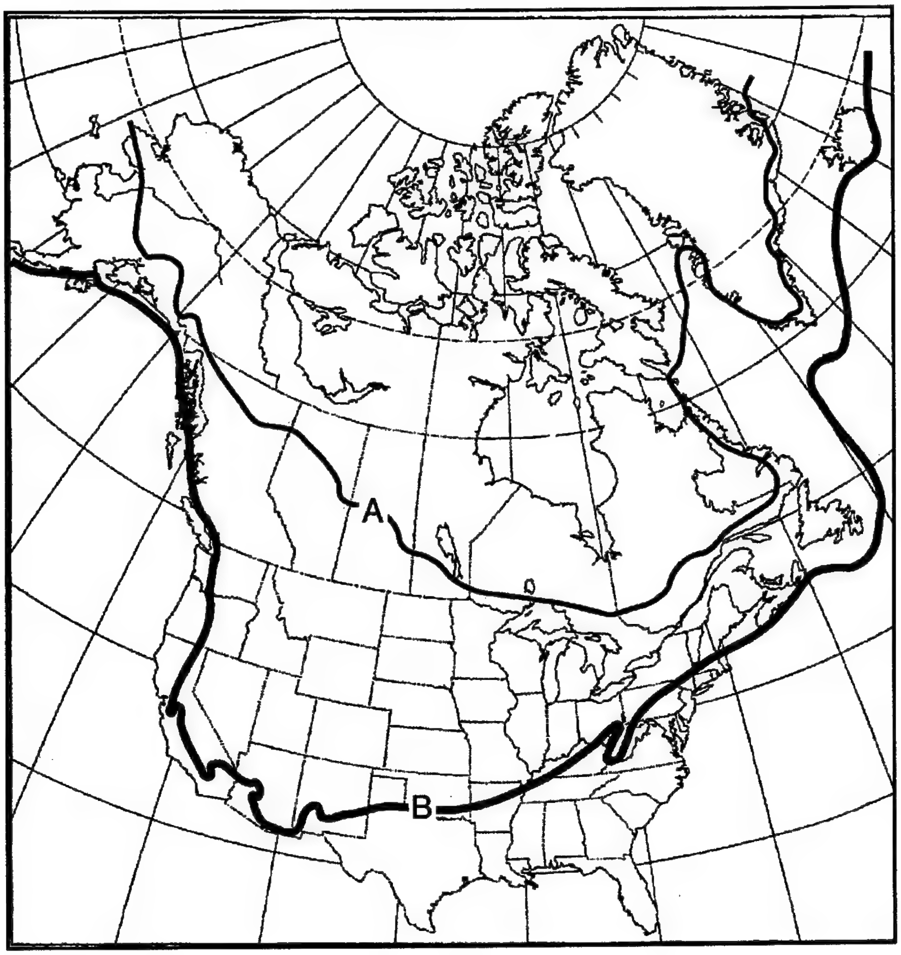

Figure 1-1. Cold regions in North America. *A-line is southernmost boundary of the area where the average temperature of the coldest winter month is -18°C (0°F) or less and ice covers navigable waters for at least 180 days of the year; B-line is the southern border of the area where the average temperature of the coldest winter month is between -18 and 0°C (0 and 32°F) and ice covers navigable waters for 100–180 days.*

walkways can become dangerously coated with ice from water spray. If not conducted cautiously, water releases from reservoirs may have the effect of dislodging downstream river ice, leading to ice runs, ice jams, and subsequent flooding.

c. Ice effects on water supply and power plants. Frazil ice and brash ice can accumulate on trash racks, thereby blocking water intakes of water supply systems, water intakes at hydropower plants, or cooling water intakes at thermal power plants. Excessively rough ice accumulations may lead to undue head losses in water supply and power canals.

d. Ice effects on river stage. A stationary river ice cover, whether an ice sheet or a jam, introduces an additional boundary and therefore increases energy losses. This translates to an increase in stage compared to open-water conditions for the same discharge. Numerical models for river hydraulics must be able to account for the effects of ice if they are to reliably describe river flows and stages. The

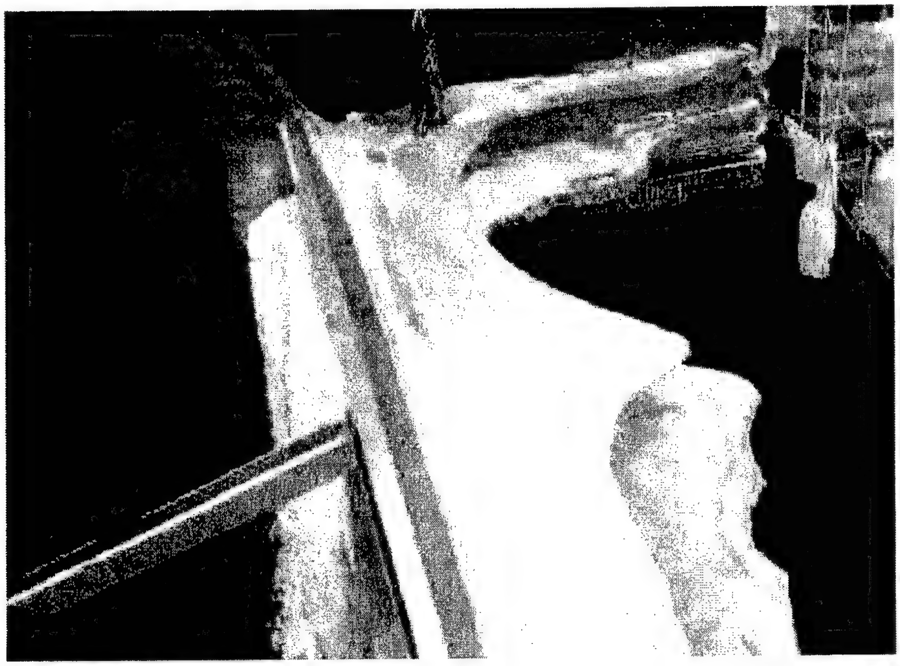

Figure 1-2. Ice accumulation on dam gates

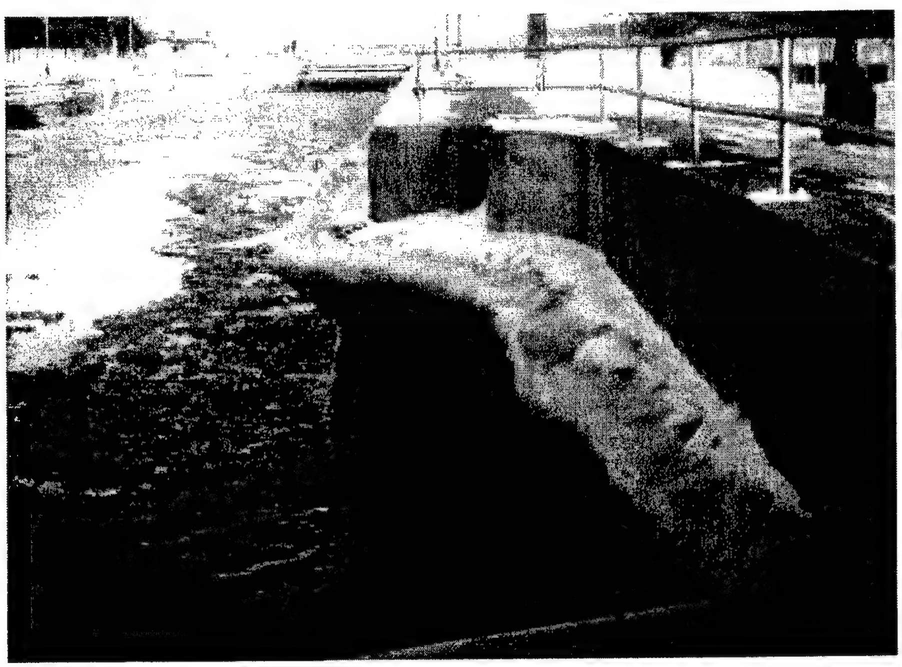

Figure 1-3. Ice collar on lock wall

resistance offered by an ice cover will lead to upstream water storage, resulting in rapid stage rise and possible flooding, and simultaneously will lead to a drop in stage and a discharge deficit downstream from the ice cover. If the stage drop is severe enough, downstream water intakes may become exposed, affecting municipal and industrial water supplies, especially during periods of drought or very low flow.

e. Ice effects on sediment transport and scour. The presence of a floating ice cover roughly doubles the wetted perimeter of a wide channel, which in turn modifies the magnitude and distribution of the velocities and, thus, the boundary and internal shear stresses. For a movable bed channel, an ice cover may, therefore, affect the bed sediment transport and the suspended sediment transport characteristics of the stream and modify the channel geometry and the bed regime. For an abrupt thickening of an ice accumulation, such as the toe of an ice jam, there may be significant bed scour because of the deflection of the flow against the bed. When this happens in the vicinity of a riverine structure, such as a bridge pier, the resulting scour may eventually cause structural failure.

f. Ice-related shore and structure damage. Damage caused by normal ice conditions in ice-prone rivers is often minor. But in more severe ice seasons, scour and ice-force damage to shorelines, pilings, piers, and levees may become significant. Unprotected earth surfaces at shorelines can be severely gouged and eroded. Particularly during ice breakup, ice floes shearing along the riverbank or striking river training structures may severely damage riprap or erode the banks. Public and private riverside structures can be weakened, distorted, or even destroyed.

g. Ice forces on structures. The design of riverine, lake, coastal, and offshore structures to be built in ice-prone areas, such as riprap installations, river training structures, docks, bridge piers, artificial islands, or oil drilling platforms, needs to take into account the potential forces exerted by ice runs at breakup or by large ice floes driven by currents or wind stresses (Figure 1-4). These forces will depend on ice thickness, ice mechanical properties, and the anticipated mode of failure of the ice (crushing, bending, or buckling).

h. Ice jam flooding. River ice jams may contribute to winter and early spring flood damage (Figure 1-5). Ice blockages in main stems and tributaries cause stages to rise and force water out of the channel over the floodplain, even when discharges are low compared to warm-water floods. Ice jam floods, while usually not as extensive as open-water floods, often take place with little or no warning. The factors and relationships that determine the probability of ice jams and ice jam flooding are more complex than those for open-water flooding. This means that the extensive statistical analysis methods applied to normal flooding phenomena are not readily applicable to ice-related occurrences. Many mitigation measures have been developed for preventing or reducing ice jam floods; these methods may be structural or nonstructural, and they may be deployed on a permanent, advance, or emergency basis. Effective Corps emergency management responses depend on fully understanding ice jam phenomena.

i. Ice effects on navigation. Ice-prone rivers in the U.S. directly serve 19 states containing 45% of the Nation's population. These rivers also serve as conduits to eight other river states and connect the U.S. heartland to world markets through the Gulf of Mexico, the St. Lawrence Seaway, and the ports of the Northwest. The principal rivers among these that generally support year-round navigation are the Ohio River (including the Monongahela and Allegheny rivers), the Illinois Waterway, and the Upper Mississippi River from Keokuk, Iowa, downstream to Cairo, Illinois (its junction with the Ohio). Elsewhere, ice formation on the Great Lakes and their connecting channels and in the Upper Mississippi River above Keokuk generally forces the suspension of commercial navigation during most of the winter season. The presence of sheet ice or brash ice in any of these waterways slows navigation considerably (Figure 1-6), may damage the hull or propulsion systems of vessels, and can cause the breakup of tows.

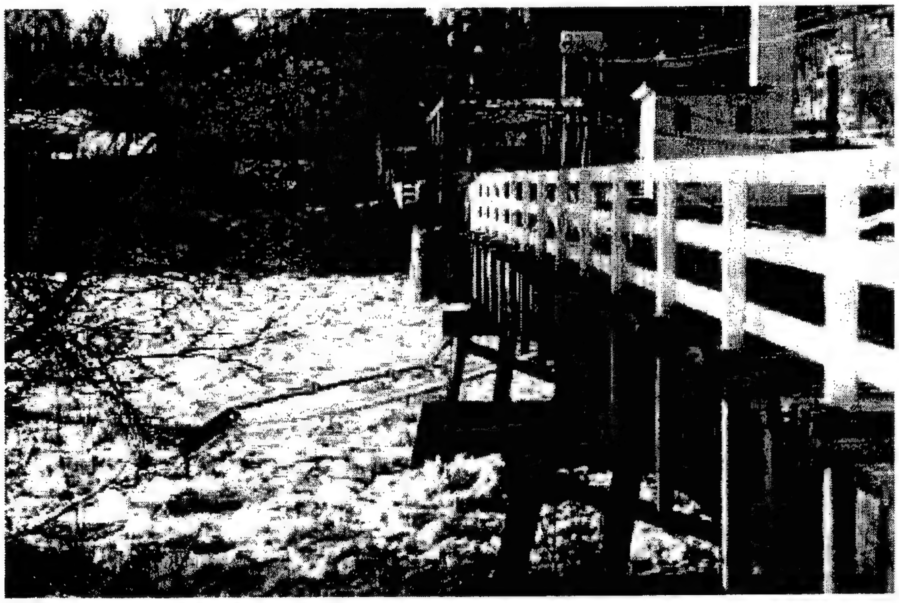

Figure 1-4. Ice action on bridge piers

Figure 1-5. Flooding caused by an ice jam

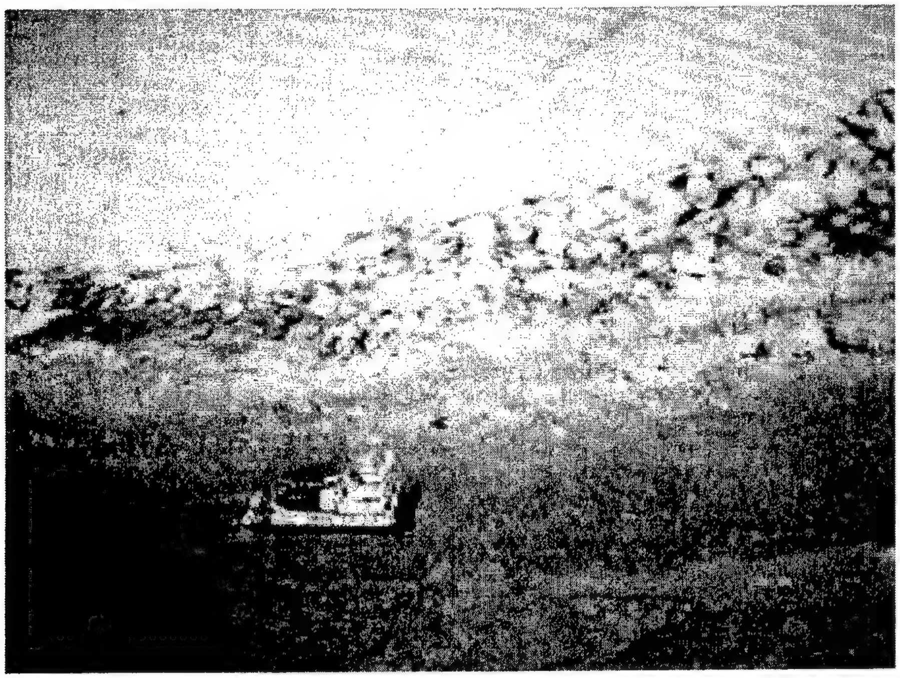

Figure 1-6. Towboat in ice

Broken ice caused by multiple vessel passages may accumulate in navigation channels or under adjacent sheet ice, further exacerbating navigation difficulties. When ice causes navigation to stop or to become significantly curtailed on these waterways, the portions of the local, regional, and national economies dependent on waterborne transportation may be adversely affected.

j. Ice problems for towboat operators. Aside from the obvious effects of ice on the navigation industry, such as increased demands on personnel, accelerated wear and tear on equipment, and increased maintenance requirements for towboats and barges, ice imposes several limitations on tow operations that directly affect the industry's efficiency. The first of these is reduced tow size. The added resistance caused by the heavy ice accumulations means that towboats are not able to push as many barges through the ice as through open water. Thus, for the same operating costs, less tonnage can be moved when ice is extensive. The next limitation is lower travel speeds. Again, this is a function of the extra energy needed to move a tow through ice accumulations, and it varies with the amount of ice in the waterway. And, finally, there are the delays at locks already enumerated, including ice restrictions on usable lock widths dictating narrower tow configurations.

k. Ice effects on industry, commerce, and the general public. When freight is delayed or stopped on ice-prone rivers by adverse ice conditions, the effects are felt by industries served by river transportation. And, as industry is affected, so also are commerce and the general public, since they rely directly or indirectly on industrial payrolls. Ice problems can curtail shipments of fuels, industrial feedstocks, finished goods, road salt, etc. These delays may lead to a range of results, from added transportation costs for alternative shipping modes to industrial plant cutbacks with associated layoffs. Delayed movement of goods leads to the depletion of reserve stockpiles, added inventory carrying costs, and extra labor costs for additional handling of bulk products. Road salt shortages may result in hazardous road conditions. Fuel shortages affect both industry and homes; often when fuel is scarce, industrial cutbacks (and layoffs) are implemented to ensure at least minimum service to hospitals and residences. Major interruptions in

industrial raw materials lead to terminating process heating, and this can result in costly shutdown and restarting expenses.

1-5. References

a. Required publications.
None.

b. Related publications.

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Part I: Ice Properties, Processes, and Problem Solutions

Chapter 2
Review of Ice Processes and Properties

2-1. Introduction

Each year, ice grows on and disappears from the Nation's rivers and lakes in tune with the cycles of nature. Unless the ice causes problems, such as flooding or blocking the arteries of commerce, few people pay more than cursory attention. Because of this, the very great variety of ways in which ice initially forms, grows, and accumulates, and finally disappears, are relatively unknown to the casual observer. Ice processes on lakes are different from those on rivers. And for both lakes and rivers, the size of the water body affects which processes take place. Ice owes its existence to the thermal processes of phase change and heat transfer, but its evolution is greatly influenced by physical and mechanical processes. Thus, this chapter introduces the wide variety of ice formation, evolution, and destruction mechanisms and identifies the principal thermal, physical, and mechanical properties that govern them.

2-2. Physical Properties of Ice and Fresh Water

a. Water properties. In ice engineering, ice is most often encountered in contact with liquid water. Therefore, it is important to be aware of the physical properties of water to fully understand the interaction of ice and water. The physical properties of greatest importance are density and specific heat.

(1) Density. The density of water (mass per unit volume) is temperature-dependent, as are many of its physical properties. The changes in water density with temperature are relatively small over the normal range of water temperature, but these small changes can have large-scale results. The primary example of this is the *thermal stratification* of lakes and reservoirs. The density change of water in response to temperature is unusual compared to almost all other substances—the density of water does not increase continuously with decreasing temperature but has a maximum at 4°C (39.2°F). A further temperature decrease causes the density of water to decrease. This density maximum has a profound effect on the thermal stratification of lakes and reservoirs in winter. The density of water as a function of temperature is reasonably well described by the following equation (Heggen 1983)

$$\rho = 1000.0 - 1.955 \times 10^{-2} |\theta - 4.0|^{1.68}$$

where ρ is the density of water in kilograms per cubic meter (kg/m^3), and θ is the temperature in degrees Celsius. In English units the equation is

$$\rho = 1.940 - 1.413 \times 10^{-5} |\theta - 39.2|^{1.68}$$

where ρ is the density of water in slugs per cubic foot (slugs/ft^3) and θ is the temperature in degrees Fahrenheit. At 0°C (32°F), the density of water is 999.80 kg/m^3 (1.94 slugs/ft^3 or 62.42 lb/ft^3 specific weight).

(2) Specific heat. Specific heat is a measure of the quantity of heat required to raise the temperature of one unit mass of fluid one unit degree under constant pressure. The specific heat of water is much larger than the specific heat of most materials. As a result, a relatively large amount of heat must be added to or

extracted from water to change its temperature. The specific heat of water as a function of temperature is described by the following equation (Heggen 1983)

$$C_p = 4174.9 + 1.6659 \left(e^{r/10.6} + e^{-r/10.6}\right)$$

where $r = 34.5 - \theta$ for $\theta < 34.5$°C, θ being the temperature in degrees Celsius, and C_p is the specific heat in joules per kilogram per degree Celsius (J/kg °C). In English units

$$C_p = 0.99716 + 3.9789 \times 10^{-4} \left(e^{r/19.08} + e^{-r/19.08}\right)$$

where $r = 94.10 - \theta$ for $\theta < 94.10$°F, θ being the temperature in degrees Fahrenheit, and C_p is the specific heat in British Thermal Units per pound per degree Fahrenheit (Btu/lb °F). At 0°C (32°F), C_p = 4218.13 J/kg °C (1.0075 Btu/lb °F).

(3) Density stratification in natural water bodies. Stratification results from differences in density and temperature occurring in a vertical section of a lake or reservoir. Lighter fluids "float" on top of denser, heavier fluids. In the summer months, the temperature of the water in a lake or reservoir will be much greater than 4°C (39°F), and warmer water will float on top of colder, denser water. As a result, in summer the water near the surface will be warmer than the water found at depth. In the winter months, when the temperature of the water in the lake or reservoir is at 4°C (39°F) or less, the less dense water will be the colder water and this water will float on top of the warmer, denser water, which has a temperature closer to 4°C (39°F). As a result, in winter the water near the surface will be colder than the water found at depth. This warmer water found at depth in lakes and reservoirs forms a "thermal reserve." If available in sufficient quantities, this reserve can be used to melt ice at the water surface by bringing up the denser, warmer water using bubblers (see Chapter 3) or mechanical diffusers.

(4) Mixing. The density difference between 0 and 4°C (32 and 39°F) is small, and it does not take much mixing action to overcome the stratification. Turbulence is a very effective mixer. All rivers, streams, and channels with any appreciable flow velocity are turbulent and therefore will be well-mixed vertically and will exhibit virtually no stratification. Therefore, there is almost no thermal reserve located at depth in flowing rivers, streams, or channels that can be exploited for melting ice. Lakes and reservoirs may be well-mixed to some depth owing to the turbulence created by wind. Ponds and shallow lakes may be well-mixed throughout their entire depth during times when there are strong winds blowing. The presence of an intact ice cover will generally protect the water below from the influence of the wind and promote stratification.

b. Density of freshwater ice. The density of freshwater ice is 916.8 kg/m^3 at 0°C (1.779 slugs/ft^3 or 57.2 lb/ft^3 specific weight at 32°F). Like most materials, ice becomes denser with decreasing temperature (at –30°C [–22°F], the density of ice is about 920.6 kg/m^3 [1.786 slugs/ft^3 or 57.5 lb/ft^3 specific weight]). The density of ice is affected by the presence of impurities, with the two most common "impurities" being air bubbles and unfrozen water. The presence of air bubbles tends to reduce the density, and unfrozen water tends to increase the density. Unfortunately, for ice found on natural water bodies, little can be said about the amount of these "impurities" without resorting to direct and somewhat difficult measurements. As a result, for engineering calculations, the approximation for the density of ice of 915–917 kg/m^3 (1.775–1.779 slugs/ft^3 or 57.1–57.2 lb/ft^3 specific weight) is probably adequate.

c. Thermal properties. The thermal properties most often needed are the thermal conductivity of ice and the latent heat.

(1) Thermal conductivity. Thermal conductivity describes the ability of ice to transmit heat under a unit temperature gradient. The temperature dependence of thermal conductivity is described by

$$k_i = 2.21 - 0.011\theta$$

where k_i is the thermal conductivity in watts per meter per degree Celsius (W/m °C) and θ is the temperature in degrees Celsius. In English units

$$k_i = 1.27 - 0.0061\ (\theta - 32)$$

where k_i is the thermal conductivity in British Thermal Units feet per hour per square foot per degree Fahrenheit (Btu ft/[hr ft^2 °F]) and θ is the temperature in degrees Fahrenheit. The thermal conductivity of ice is greater than that of concrete (0.81–1.40 W/m °C {0.47–0.81 Btu ft/[hr ft^2 °F]}) and wood (0.14–0.21 W/m °C {0.08–0.12 Btu ft/[hr ft^2 °F]}) but much less than that of metal (for example, copper 388 [224], aluminum 209 [120], and steel 49 [3]). Ice is a not a great insulator, but it is not much of a heat conductor either. The thermal conductivity of ice is significantly influenced by air bubbles and the inclusion of unfrozen water. But as with the density determination, the amount of both of these impurities in ice in natural water bodies is usually not known, and as a result their influence is usually ignored.

(2) Latent heat. Pure water freezes at 0°C (32°F) under standard atmospheric pressure. When water freezes, 333.4 J/g (143.3 Btu/lb) of latent heat is released. This is a substantial amount of heat, especially when compared to the 4.217 J/g (1.813 Btu/lb) it takes to change the temperature of water 1°C (1.8°F).

2-3. Mechanical Properties of Freshwater Ice

Mechanical properties are important parameters that control the forces that ice may exert upon structures and the deformation of ice under load. Ice is a complex material whose behavior under load can range from brittle to ductile, depending on its structure, the rate of load application, and temperature. Because of these factors, the values of ice properties also vary with the measurement techniques and conditions. Only a brief summary of the mechanical properties of freshwater ice is presented below. The reader interested in ice rheology and ice mechanics should consult more specialized texts such as Pounder (1965), Michel (1978), or Ashton (1986).

a. Ice strength. Strength is defined as the maximum stress that a test specimen can support immediately before failure. Its value will thus depend on the mode of failure (e.g., bending or flexure, crushing or compression, shear), the type of failure (namely brittle or ductile), the presence of flaws in the ice, and, as already mentioned, the test technique. In the following, only brittle failure will be considered, since it corresponds to the relatively high loading rate more commonly associated with ice impact on structures when driven by water flow or wind.

(1) Bending or flexural strength. The ice bending or flexural strength is the maximum stress that an ice sheet or ice floe can withstand when subjected to a vertical load at the edge of the ice sheet, e.g., when riding up an inclined slope or striking an inclined bridge pier. A number of studies have measured ice

flexural strength (Frankenstein 1968, Lavrov 1969, Gow 1977). From these, the expected bending strength of competent, columnar freshwater ice ranges from a low of 0.5 MPa (70 psi) for relatively large specimens tested by the cantilever beam method to a high of 1.2 MPa (170 psi) for small, simple beam specimens. This range of values also reflects differences in results obtained depending on whether the tests were conducted with the top of the ice under tension or the bottom of the ice under tension and the corresponding variation in crystal size.

(2) Crushing or compressive strength. The ice compressive strength is the maximum stress before failure that ice can withstand when subjected to in-plane loads, i.e., normal to the ice floe thickness, as when being pushed against a vertical surface or bridge pier. The main factors that affect the crushing strength of ice are the crystal size, the rate of loading (strain rate), and the ice temperature. On the average, for columnar ice and snow or frazil ice at about –10°C (14°F) and in the brittle range of failure, i.e., for relatively high rate of loading, the crushing strength is in the range of 8 to 10 MPa (1.1 to 1.5 kpsi). Michel (1978) gives the following equation for estimating the ice crushing strength

$$\sigma = 9.4 \times 10^5 \left(d^{-1/2} + 3\ |\theta|^{0.78}\right) \tag{2-1}$$

where

σ = crushing strength (pascals)

d = crystal size (centimeters)

θ = temperature (degrees Celsius).

(3) Breakthrough loads. The bearing capacity of ice is discussed in some detail in Chapter 8. For short-term duration loads, the allowable load P that a floating ice sheet can support is proportional to the square of the ice thickness h, that is

$$P = A\ h^2. \tag{2-2}$$

For most practical purposes, the value for A can be taken as 1/100 when P is expressed in metric tons (1000 kg) and h in centimeters (A can be taken as 1 when P is expressed in meganewtons and h in meters), and for P in tons and h in inches, then A can be taken as 1/16.

b. Elastic modulus. The elastic modulus E describes the relationship between stress and strain. For the case of ice, the elastic modulus has been found to depend on the ice temperature, crystal structure, and the rate of stress application. Also, creep in ice can occur soon, especially at high stress levels, requiring that strain be measured "extremely quickly after the application of the stress" (Ashton 1986). As for the other mechanical properties of ice, the measured values of the elastic modulus also depend on the measurement techniques. As a result, estimates of the elastic modulus can range widely, and values estimated or measured in the field for the elastic modulus of intact freshwater ice range from about 0.4 to 9.8 GPa (55 to 1350 kpsi). The elastic modulus of ice grown in large laboratory tanks ranges from about 4.3 to 8.3 GPa (600 to 1150 kpsi), whereas the elastic modulus of small laboratory specimens is typically higher. Values for extensively cracked or deteriorated ice may be much lower.

c. Characteristic length. The characteristic length L_c of a floating ice sheet is a measure of the extent of the zone of deformation when the ice is subjected to a vertical load. It also governs the initial size of ice

floes resulting from the breakup of a sheet ice cover. This parameter is expressed in terms of the ice thickness h and modulus of elasticity E by

$$L_c = \left[\frac{E h^3}{12 \gamma \left(1 - \nu^2\right)} \right]^{1/4} \tag{2-3}$$

where γ is the specific weight of water and ν is the Poisson's ratio of ice, usually taken to be 0.3. From elastic analysis, the radius of the area of deformation is approximately equal to 3 characteristic lengths. Field measurements (Sodhi et al. 1985) have shown that the characteristic length of competent freshwater ice is about 15 to 20 times the ice thickness, with the higher ratio corresponding to cold ice and the lower values for warm ice in late winter or early spring.

d. Field measurements. There is no simple, reliable method to measure the compressive strength of ice in the field. It is often necessary to collect ice samples for testing in the laboratory under controlled conditions. The flexural strength and the elastic modulus can, on the other hand, be measured in the field with a minimum of equipment (IAHR 1980) using one of the techniques described below.

(1) Cantilever beam. A cantilever beam of length L (= 5 to 8 h) and width B ($\cong$ 2 h) is cut in the ice sheet (Figure 2-1a). A load P is applied to the tip of the beam and the corresponding deflection δ is measured. The elastic modulus E is given by

$$E = \frac{4}{B} \left(\frac{L}{h} \right)^2 \frac{P}{\delta}. \tag{2-4a}$$

If P' is the failure load of the cantilever beam, the flexural strength is calculated by

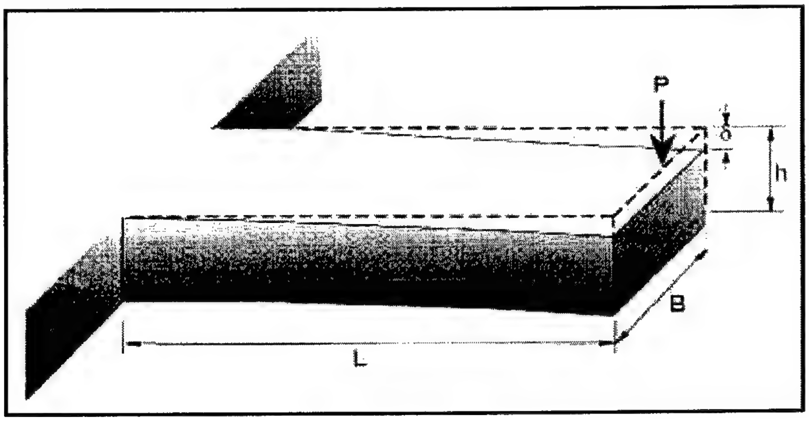
$$\sigma_b = 6 \, \frac{P'L}{Bh^2}. \tag{2-4b}$$

To make the results as reliable as possible, the saw cuts at the root of the cantilever beam should be rounded to avoid local stress concentration and resulting early failure of the beam.

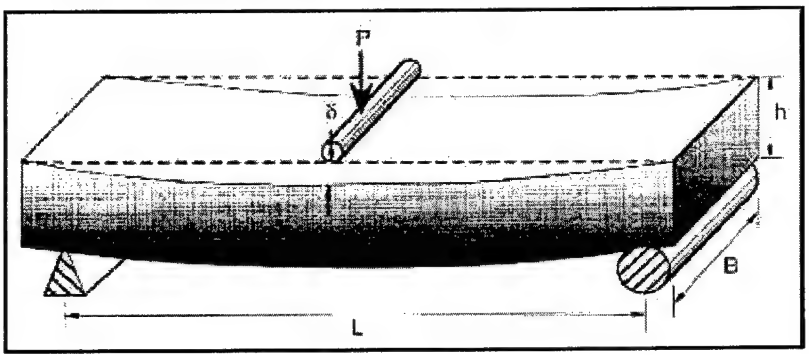
(2) Simple beam. A beam of length L and width B cut from the ice sheet is placed on two supports and loaded in the beam center with a load P that yields a deflection δ (Figure 2-1b). The corresponding value of the elastic modulus is

$$E = \frac{P}{4 B \delta} \left(\frac{L}{h} \right)^3. \tag{2-5a}$$

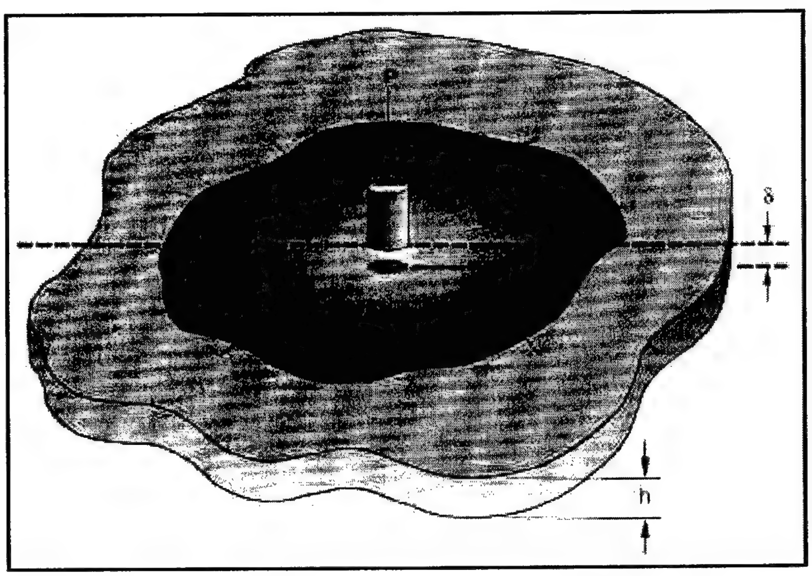
The flexural strength is obtained for the maximum load at failure P' by



a. Cantilever beam method.



b. Simple beam method.



c. Plate deflection method.

Figure 2-1. Determination of the mechanical properties of ice

$$\sigma_b = \frac{3P'L}{2Bh^2}. \tag{2-5b}$$

(3) Plate loading. The characteristic length L_c of ice can be directly measured by loading an ice sheet with a load P (e.g., a drum that can be filled with water from a safe distance away) and measuring the corresponding plate deflection δ as near the edge of load application as possible, as shown in Figure 2-1c.

$$L_c = \sqrt{\frac{P}{8\gamma\delta}} \tag{2-6}$$

where γ is the specific weight of water. For Equation 2-6 to be valid, the ratio of the radius a of the load area to the characteristic length should not exceed 0.2, i.e.

$$\frac{a}{L_c} \approx \frac{a}{17h} \le 0.2. \tag{2-7}$$

Stated another way, a should not exceed 3 to 4 ice thicknesses.

2-4. Frazil Ice

Frazil ice is formed in turbulent, supercooled water. Supercooled water is at a temperature below its equilibrium freezing point; for pure water the freezing point is, by definition, 0°C (32°F) at atmospheric pressure. Supercooling takes place in lakes and rivers in turbulent, open-water areas when the air temperature is significantly less than 0°C (32°F). Usually an air temperature of –8°C (18°F) or lower is required. The requirement for open water can be understood by noting that, if the water surface is covered with ice, the temperature at the ice/water interface must be at the equilibrium freezing point, and all heat transfer from the water would stop when the water cooled to 0°C (32°F). As a result, the formation of frazil is always associated with open water. The level of supercooling should not be overestimated; it will usually not exceed several hundredths of a degree Celsius, and in no case will it exceed 0.1°C (0.18°F). As a result, supercooling is detectable only with laboratory-grade thermometers. Frazil ice appears first as small crystals (0.1 millimeter to several millimeters, 0.004 inch to one or two tenths of an inch) that are distributed more or less uniformly throughout the region of turbulence. In rivers, for example, this is likely to be throughout the entire depth. Each crystal starts out as a perfect disk, whose major diameter is 10 to 12 times its thickness. This disk shape is the form by which frazil is chiefly known, but, with time, frazil ice evolves through a number of processes to form larger and larger ice masses. Eventually, it will become a stationary, floating ice cover that may be many kilometers (miles) long.

a. Frazil ice formation. During the formation stage, the initial frazil ice crystals are created. Formation is characterized by supercooled water, turbulent flow, the rapid growth of disk-shaped crystals, and the creation of new crystals by secondary nucleation (explained below). The length scales of the ice associated with this stage range from several micrometers to perhaps a few millimeters (i.e., between a hundredth and a tenth of an inch). This stage usually takes place during cold periods when the heat loss from the open water surface is intense.

(1) Nucleation. It is now known that the frazil crystals do not "spontaneously" appear through nucleation in the water column. Nucleation is a general term, referring to the formation of a new phase of a substance from a parent phase. In our case, the parent phase is obviously water, and the new phase that is appearing is, of course, ice. We know now that frazil ice crystals are formed from *seed crystals*, which are ice crystals introduced from outside the natural water body. Seed crystals can come from a number of different sources: vapor evaporating from the water surface, upon encountering cold air, can sublimate into ice crystals, which fall back onto the water surface and are entrained by the turbulent motion of the flow; small water droplets generated by breaking waves; bubbles bursting at the water surface; splashing; and snow and sleet. But seed crystals are not the whole story.

(2) Secondary nucleation. It is observed that once a very few seed crystals are introduced into turbulent supercooled water, very quickly many new crystals are created through *secondary nucleation.* Collisions of existing crystals with hard surfaces (including other crystals) is thought to be the main mechanism through which new frazil ice crystals are formed. These new crystals can then further increase the rate of secondary nucleation with a multiplicative effect. Because the frazil ice crystals are suspended in supercooled water, they are also growing in size. The water temperature will dynamically reflect the balance of the latent heat released by the growing crystals and the heat transfer from the water surface. Eventually, the rate of latent heat released is enough to return the water temperature to the ice–water equilibrium temperature (0°C [32°F]).

b. Frazil ice evolution and transport. Frazil ice evolves and is transported after it forms. Frazil evolves in form largely from the individual crystals joining together to form larger masses. The evolution of frazil is characterized by water more or less at the equilibrium temperature, and frazil in the form of *flocs*, *anchor ice,* and *floes*. The length scales of the ice associated with this stage range from several millimeters to many meters (i.e., a fraction of an inch to tens of feet). The frazil is largely moving under the influence of the flow velocity of the river or stream, generally at the surface. After cold nights, it is typical to see *frazil slush*, formed of frazil flocs, moving along at the water surface of northern rivers and streams. This ice may travel long distances, moving for many days and may eventually form large moving floes. Eventually, through a process termed *juxtaposition*, the frazil floes may form stationary, floating ice covers of uniform thickness that may be quite large and last for the entire winter season. Other configurations of ice covers may form by a variety of mechanisms, depending on the dynamics of the frazil ice upon its arrival at the site of stationary ice, and depending on the hydraulic conditions at the cover's leading edge. Frazil slush and floes may be entrained in the flow beneath the initial cover to form thicker accumulations. In extreme cases, these floating covers can become very thick, as in the relatively rare instance where a *hanging dam* forms. Frazil ice may be deposited on or eroded from the underside of the cover throughout the winter. The crystal structure of ice covers formed from frazil ice reflects its origin, and the ice crystals tend to be small and randomly oriented.

c. Problems caused by frazil ice. Frazil ice can cause a number of problems. If areas of streams or channels remain open for long periods during cold weather, large amounts of frazil ice can be formed, carried downstream by the flow velocity, and eventually deposited in a relatively slow velocity reach of the river to form a *freezeup ice jam.* Freezeup ice jams can block substantial portions of the river cross section. This blockage may raise upstream water levels enough to cause flooding, or may serve as the site of a *breakup ice jam* later in the winter season. Upstream water levels may also be raised if large amounts of frazil ice are deposited on the channel bottom as *anchor ice* to form *anchor ice dams*. Anchor ice dams are relatively rare, and usually occur in steep, shallow rivers and streams. Water intakes can experience significant problems with frazil ice if they are operated when the water is supercooled. The crystals in the supercooled water will be growing in size and will stick to any object they contact—including intake trash

racks—as long as these objects are at a temperature below freezing. Given the effective heat transfer rates provided by flowing water, any object in the water that is not heated will quickly be at the temperature of the supercooled water and will accumulate frazil. Sufficient frazil can accumulate on the trash rack to effectively block it and completely stop the flow of water into the intake, often with severe consequences.

d. Control of frazil ice. An intact, stable ice cover will always prevent the production of frazil ice by "insulating" the water surface and preventing the large heat loss rates responsible for supercooled water. If an ice cover can be successfully created and kept in place over a reach of a river that is normally open during periods of cold weather, frazil ice problems can be completely avoided or substantially reduced. The techniques for creating and maintaining a stable ice cover are described in Chapter 3. Another technique for preventing supercooled water is to mix "warm" water with the supercooled water and raise the water temperature to the ice–water equilibrium temperature, or slightly above. This technique is especially effective near water intakes, where the quantity of warm water required can be modest. Finally, if the actual production of frazil ice cannot be controlled, mechanical removal of the frazil, using techniques described elsewhere in this manual, may be the only recourse.

2-5. Thermal Ice Growth

a. Static ice formation. Ice formation on water in which the flow velocity plays no role is called static ice formation. This includes ice formed on lakes and ponds during periods of low winds, and on rivers and streams in which the flow velocity is approximately 0.3 m/s (1 ft/s) or less. Static ice formation starts in a very thin layer of supercooled water at the water surface and is probably initiated by the introduction of seed crystals. The ice grows at the ice/water interface as a result of heat transfer upward from the interface, through the ice, to the atmosphere. Ice grows in hexagonal crystals with three *a* axes of symmetry in what is called the basal plane, and one *c* axis perpendicular to the basal plane. The orientation of the ice crystals in a static ice cover can vary, depending on the initial formation process. However, once an initial ice cover is formed, continued thermal growth of the initial ice crystals tends to favor the development of vertical *c* axes. Often, ice crystals in a static ice cover look like pencils with the "c" axes as the leads, and are called *columnar.* Because the impurities in the water are "pushed" to the boundaries of columnar crystals during growth, a relatively high concentration of impurities is trapped between the crystal boundaries. Owing to the trapped impurities, melting begins at the crystal boundaries during warm periods and a phenomenon called *candle ice* often develops. In candle ice, innumerable single crystals are no longer frozen together, but rather are leaning on each other for support. A small impact, such as a wave, or a well-placed kick, can collapse the entire mass. Another form of ice found during static ice growth results from the presence of a snow cover on the ice and is called *snow ice.* Snow ice is formed when the weight of a snow cover on the ice sheet is sufficient to depress the ice and cause water to flood up through cracks and saturate the lower layers of the snow. Snow ice is granular, opaque, and white, and it has small, randomly oriented crystals.

b. Thermal balance of ice covers. The thermal balance of ice covers is found by summing all the modes of heat transfer between the ice cover and the atmosphere, and between the ice cover and the water below (Ashton 1986). One important aspect of the thermal heat balance is the heat input through solar radiation (sunlight), especially in the spring, when the hours of daylight are increasing. The ratio of the reflected sunlight to the incident sunlight is defined as the *albedo* of the surface. (An albedo of unity indicates that all of the solar radiation is reflected, while an albedo of zero means that all of the radiant energy is absorbed.) Ice covers that look "white" tend to have high albedos. For example, an ice surface covered with fresh snow can have an albedo of 0.9; ice covers composed of snow ice can have albedos as high as 0.6 to 0.8. In contrast to this, ice covers that are composed of clear columnar ice ("black" ice) may have

albedo values as low as 0.2. An attractive and relatively easy way to modify the thermal balance of ice, especially to promote the melting and weakening of the ice cover to reduce the threat of ice jam flooding, is to decrease its albedo by applying a dark material or *dust* to the top surface to increase the absorption of solar radiation. Depending on the type of dust used and amount applied, the albedo can be reduced to 0.15 or 0.2.

c. Estimating thermal ice growth. Predicting the thickness of a natural ice cover attributable to thermal growth is a classic problem of ice engineering. The differential equation describing the thermal growth rate can be formulated by assuming the following:

- That the ice is a homogenous, horizontal layer.
- That the ice is growing only at its horizontal interface with the water.
- That the thermal conditions in the ice are quasi-steady.
- That the heat flux from the water is negligible.
- That the heat fluxes are in the vertical direction only.
- That the heat loss rate from the ice surface to the atmosphere is a linear function of the temperature difference between the ice surface and the air.

Under these assumptions, the heat transfer rate through the ice cover to the atmosphere is equivalent to that of a steady heat flux through a composite slab. The thermal growth rate of the ice is found as

$$\frac{\partial h}{\partial t} = \frac{1}{\rho\lambda} \frac{(T_m - T_a)}{\left(\frac{h}{k_i} + \frac{1}{H_{ia}}\right)} \tag{2-8}$$

where

h = ice thickness

T_m = temperature at the water/ice interface (assumed to be the ice–water equilibrium temperature, or 0°C [32°F])

t = time

T_a = air temperature

k_i = thermal conductivity of the ice

H_{ia} = heat transfer coefficient from the ice surface to the atmosphere

ρ = ice density

λ = ice latent heat.

Although Equation 2-8 is nonlinear, it is readily solved to yield the following "standard" model of ice thickness as a function of air temperature

$$h_j = \sqrt{(B + h_k)^2 + 2A(U_j - U_k)} - B \tag{2-9}$$

where

h_j = calculated ice thickness on day j

h_k = ice thickness on day k, either observed or calculated (note that $j > k$, meaning that day j occurs after day k).

$$A = \frac{k_i}{\rho\lambda}$$

$$B = \frac{k_i}{H_{ia}}$$

$$U_j = \sum_{i=1}^{j} (T_m - T_{ai})$$

$$U_k = \sum_{i=1}^{k} (T_m - T_{ai})$$

U_j = Accumulated Freezing Degree-Days (AFDDs) recorded between the onset of freezeup (day 1) and day j

U_k = AFDDs recorded between the onset of freezeup and day k (note that $U_j \geq U_k$).

If the heat conduction through the ice cover is the controlling rate in the overall energy flux, then B can be ignored and, if the initial ice thickness is assumed to be zero, then the classic result is found

$$h_j = \alpha\sqrt{U_j} \tag{2-10}$$

where

$$\alpha = \sqrt{\frac{2k_i}{\rho\lambda}}\ .$$

Typical values for α are presented in Table 2-1. In this case the ice thickness is proportional to the square root of the accumulated freezing degree-days.

d. Remarks. It is not surprising that, for natural ice covers, the assumptions upon which the standard model is based may not always hold true, and other processes, not included in the standard model, may also influence the thermal growth rate of the ice. For example, the presence of snow on the

Table 2-1
Typical Values of α (after Michel 1971)

Ice Cover Condition	α*	α†
Windy lake w/no snow	2.7	0.80
Average lake with snow	1.7-2.4	0.50-0.70
Average river with snow	0.4-0.5	0.12-0.15
Sheltered small river	0.7-1.4	0.21-0.41

* AFDD calculated using degrees Celsius. The ice thickness is in centimeters.
† AFDD calculated using degrees Fahrenheit. The ice thickness is in inches.

ice cover may influence the heat transfer rate from the ice surface to the atmosphere. In theory, this influence could be accounted for in the standard model if the snow depth and the snow thermal conductivity were known. The ice surface may also be flooded if the weight of the accumulated snow is greater than the buoyant force of the ice cover. This will cause part of the snow to become saturated by water flowing upward through cracks in the ice. This saturated snow is able to freeze relatively rapidly, forming snow ice. In addition, the heat flux from the ice surface to the atmosphere is composed of several modes of heat transfer, including shortwave radiation, longwave radiation, evaporation, and sensible heat loss. The actual heat transfer rate is only approximated by the relationship included in the standard model. As a result, H_{ia}, the heat transfer coefficient, may not be a constant but may vary with the meteorological conditions. Given all this, however, the standard model represented by Equation 2-9 still represents a good, practical model of ice growth. To go beyond the standard model requires an extensive data collection, and, to date, there has been no indication that the additional effort would be rewarded by a more accurate model.

2-6. Dynamic Ice Cover Formation

When an ice cover's growth is dominated by the interaction between the transported ice pieces and the flowing water, the cover is said to form dynamically. This is the counterpart of the thermal formation and growth described earlier. Almost all river ice covers are formed dynamically. All ice covers that form in this way progress upstream from an initiation point as ice is brought to the leading upstream edge of the ice cover by the flow of the river. Many different and separate processes may occur at the leading edge, depending on the hydraulic flow conditions and the form of the arriving ice. The various processes at the leading edge are described in a general way in the following.

a. Bridging. At very low flow velocities and relatively high concentrations of surface ice, it may be possible for the ice cover to spontaneously arch across the open width of the channel and stop moving. It is generally not possible to predict where these bridging locations will be without historical knowledge. To assure the initiation of an ice cover at a specific location, ice control booms or hydraulic control structures, or both, may be necessary.

b. Juxtaposition. At relatively low flow velocities, ice floes arriving at the leading edge may simply come to a stop and not underturn. In this way the ice cover will progress upstream by juxtaposition. The maximum flow velocity at which juxtaposition happens depends on the floe geometry and the channel depth. Generally, ice control booms will function properly only if juxtaposition of the arriving ice is possible.

c. Underturning of floes. At higher flow velocities, the arriving floes may not be stable but may instead underturn. If the flow velocity is not too high, these underturned floes will remain at the leading edge of the ice cover.

d. Ice cover shoving. Shoving in the ice cover can happen over a wide range of flow velocities. The cover collapses in the downstream direction and becomes thicker if the forces acting on it exceed its ability to withstand those forces. The strength of an ice cover formed from many separate pieces of ice increases with its thickness, so that when shoving takes place, the strength of the ice cover is increased. An ice cover may repeatedly shove and thicken as it progresses upstream. If the ice cover is treated as a "granular" material, its strength characteristics and its final thickness can be estimated.

e. Under-ice transport of floes. At relatively high flow velocities, the ice floes arriving at the leading edge of the ice cover may be underturned and transported under the ice cover for considerable distances. At this point, further upstream progression may be halted until the deposition of the floes somewhere downstream of the leading edge reduces the channel conveyance sufficiently to cause the upstream water levels to rise and the flow velocities at the leading edge to be reduced.

f. No ice cover progression. The ice cover will stop progressing upstream if the flow velocities at the leading edge remain too high. In this case open water will remain upstream of the leading edge throughout the winter season. This will result in the production of frazil ice in the open-water area all winter, which may lead to the formation of freezeup jams or other problems downstream.

2-7. Ice Cover Breakup

Breakup transforms a completely ice-covered river into an open river. Two extreme forms of breakup bracket the types of breakup commonly found throughout most of North America. At one extreme is *thermal meltout.* During an ideal thermal meltout, the river ice cover deteriorates through warming and the absorption of solar radiation and melts in place, with no increase in flow and little or no ice movement. At the other extreme is the more complex and less understood *mechanical breakup.* Mechanical breakup requires no deterioration of the ice cover but rather results from the increase of river discharge. The increase in flow induces stresses in the cover, and the stresses in turn cause cracks and the ultimate fragmentation of the ice cover into pieces that are transported by the channel flow. Ice jams take place at locations where the ice fragments stop. Severe and sudden flooding can result when these ice jams form or when they release. Actual breakups take place most often during warming periods, when the ice cover strength deteriorates to some degree and the flow in the river increases because of snowmelt or precipitation. Therefore, most river ice breakups actually fall somewhere in between the extremes of thermal meltout and mechanical breakup. As a general rule, the closer that a breakup is to being a mechanical breakup, the more dramatic and dangerous it is because of the increase in flow and the large volume of fragmented ice produced.

a. Thermal meltout. Every river in North America will experience a thermal meltout every spring unless a mechanical breakup occurs first. Thermal meltouts will not take place at all points on a river simultaneously, but will occur at different locations at different rates depending on the latitude, local climate, and ice exposure. Thermal meltouts happen because of heat transfer into the ice cover by convection to its underside from the water, by convection from the warm air to its top, and radiation, both longwave (infrared) and shortwave (sunlight). The transfer of heat from the water to the underside of the ice cover can be very substantial, especially if there is open water upstream that provides an area in which the flowing water can absorb heat from the atmosphere. In almost all cases, the albedo of open-water areas

will be much less than the albedo of the ice cover. As a result, the open-water areas will absorb more solar radiation than ice-covered areas. When the flowing water passes under the ice cover, a portion of the extra heat provided by this lower albedo will be available to melt its underside. Generally, the albedo of snow on the ice surface or snow ice will be quite large and little solar radiation will penetrate the ice cover. The creation of meltwater on the surface will drastically lower the albedo and help the ice absorb sunlight. The ice cover can also deteriorate internally without much of a loss of thickness if solar radiation is able to penetrate it. The absorbed solar radiation causes melting in the interior of the ice that results in a loss of structural integrity of the cover, as described previously in paragraph 2-5a. This is most likely to happen if the ice cover is composed of columnar crystals. Fine-grained ice covers, composed of snow ice or frazil ice, are much less susceptible to internal deterioration through absorption of solar radiation.

b. Mechanical ice cover breakup. Breakup does not happen simultaneously everywhere along a river network. Often breakup occurs first on smaller tributaries, and then proceeds haphazardly to the main stem rivers. This can result in severe ice jams at the confluence of tributaries and the main stems. Breakup can progress upstream or downstream, depending on the local weather and the flow direction of the river. On rivers that flow north, or flow from a warmer area to a colder area, breakup often progresses from upstream to downstream. Generally, if downstream locations release their ice first, fewer ice jams will result than if the breakup front progresses from upstream to downstream. Every breakup is different, but there are a few broad similarities in the sequence of a breakup that can be described. The mechanical breakup always occurs in response to an increase in flow in the river, with a corresponding increase in stage.

(1) Formation of shore cracks. Shore cracks are longitudinal cracks running parallel to the banks of the rivers. Shore cracks form as a result of changes in water level. Controlling factors are the material properties of the ice, ice thickness, channel width, and the type of attachment of the ice cover to the channel bank (hinged or fixed). Only a small increase or decrease in discharge is necessary to cause shore cracks, and they are usually common soon after runoff into a river has begun to increase. The presence of shore cracks does not necessarily indicate the immediate onset of breakup. They may be present throughout the winter season.

(2) Cracking of the ice sheet into individual floes. Transverse cracks (across the channel) will appear soon after the river stage has begun to increase. The first cracks will generally create relatively large ice floes, a river-width wide, and many river-widths long, but sometimes the ice covers are immediately broken into much smaller floes. The actual mechanisms responsible for creating the individual floes have not yet been positively identified.

(3) Movement of floes. As the stage continues to increase, the ice floes will begin to move. If the floes are relatively large, they may be held in place by sharp bends, constrictions, bridge piers, etc., until a substantial increase in stage is reached. If the floes are relatively small, and there are no constraints, they may begin to move after a small stage increase. As a rule of thumb, the stage must rise 1-1/2 to 3 times the ice thickness before the ice moves. Once the floes begin moving, they are quickly reduced in size, eventually attaining a diameter that is roughly 4 to 6 times the ice thickness.

(4) Formation of ice jams. Ice jams form when the moving ice floes reach a location in the river where its ice transport capacity is exceeded. This is most likely at places where an intact ice cover remains, the slope of the river decreases, a geometric constraint exists, etc. At these locations, the ice stops moving and jams. This type of ice jam is a *breakup ice jam.* Ice jams substantially reduce the channel flow conveyance. As a result, water levels upstream of an ice jam can rise substantially and quickly, causing flooding and transporting ice into the floodplain. The probable maximum thickness and roughness of ice jams can be estimated and used to estimate the probable flood stages (see Chapter 4).

2-8. References

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None.

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Chapter 3
Ice Control

3-1. Introduction

a. Purpose. The practice of ice control is aimed at influencing or modifying the behavior of ice in the annual cycle of ice formation, growth, and decay. For example, ice control may be employed to promote ice cover formation or stabilization at a time much earlier than it would occur under normal conditions. In other words, ice control can lead to the formation of a stationary ice cover where the natural ice condition at a given time in the winter may be open water and the continuous production of frazil ice, causing freezeup ice jams downstream. In some cases, it is possible to control the timing and location of ice breakup. Some forms of ice control are used to prevent ice formation or limit ice thickness, with resulting benefits for navigation, for structures subjected to ice forces, or for downstream areas liable to breakup ice jams.

b. Approach. Ice control is divided into two broad areas: mechanical control and thermal control.

(1) Mechanical control focuses on ice retention: creating a stationary ice cover or retaining moving ice in a chosen location. Most of these techniques are intended to influence the beginning of the ice-formation–growth–decay cycle, but a few are designed to address the ending portions of this cycle. Most mechanical ice control is achieved by flexible, often seasonally deployed, structures, such as ice booms, or by rigid (or semirigid) structures, such as weirs, artificial islands, piers, groins, cribs, or dolphins (Tuthill 1995). An ice boom is a barrier made from floating pontoons or timbers anchored by chain and wire rope. Booms are used to initiate an ice cover, thereby minimizing frazil ice generation. Booms also benefit navigation and hydropower production by retaining ice later in the winter and early spring. Examples of rigid structures are the ice piers that have been constructed on the Ohio River above Cincinnati. These are simply large bridge piers or cells placed fairly close together to slow, stop, or redirect ice flow. A tow may take shelter below these piers during an ice run. In general for navigable waterways, mechanical ice control measures need to permit the continuance of navigation during winter (Perham 1988a). For example, navigable ice booms provide an open section to allow vessel passage. Most major inland rivers have a 2.7-meter (9-foot) navigation depth and handle barge traffic. Harbors and fleeting areas on most of these navigable rivers are present in almost any type of river reach, including the inside and outside of bends, at confluences, and in straight reaches. Structural ice control measures would most likely have to be located outside of the harbors and fleeting areas to permit free access of barge tows to moorings and wharfs and to accommodate cross-stream traffic (Perham 1988b).

(2) Thermal control is employed to maintain open water where ice covers would normally occur, or to at least limit the thicknesses of ice that normally would grow. Air bubblers, for example, are used to bring up warmer water from some depth to melt ice or at least retard its growth. Waste heat, introduced to a river, harbor, or lake from thermal power plants or industrial processes, is also an effective means of thermal control. (An offshoot of air bubblers is a high-flow air system, which releases large quantities of air at some depth to induce diverging horizontal water velocities at the surface. These surface currents prevent ice or debris from passing or they deflect ice or debris away from critical areas. These systems are discussed in Part III, Chapter 19.)

Section I
Mechanical Ice Control

3-2. Ice Control Using Flexible Structures

Ice booms are the most widely used type of flexible sheet ice retention structure. The first such structures were long booms of logs chained or wired end to end into a long line across a water body. The logs provided flotation as well as structural strength. Sometimes, several logs were bolted side by side to obtain sufficient flotation. The booms were anchored onshore and to boom docks (rock-filled timber cribs) in midstream. The trash booms used at hydroelectric plants to keep floating debris from power canals are similar and may have been the first to use a continuous wire rope for structural strength. The most common type of ice boom consists of large floating timbers held in place by a wire rope structure and buried anchors (Figure 3-1). The weight of the wire rope structure and junction plates is carried by supplemental floats. Ice booms have been installed primarily by hydroelectric power companies to minimize the volume of ice impinging on their trash racks, to minimize the formation of frazil ice, and to keep head losses to a minimum. The boom or series of booms collects floating ice and accelerates the formation of an ice cover upstream. When the discharge is controlled, as at a power station, a decrease in flow will further accelerate ice cover formation. Booms have been installed to restrain and thereby minimize the ice contribution to ice jams or ice pileups on shore that can block water intakes. Booms assist navigation by holding brash ice and floes in place so that they do not flow downstream and block narrow channels. Booms are not intended to restrain ice at breakup, but under quiescent hydraulic conditions they may serve this purpose.

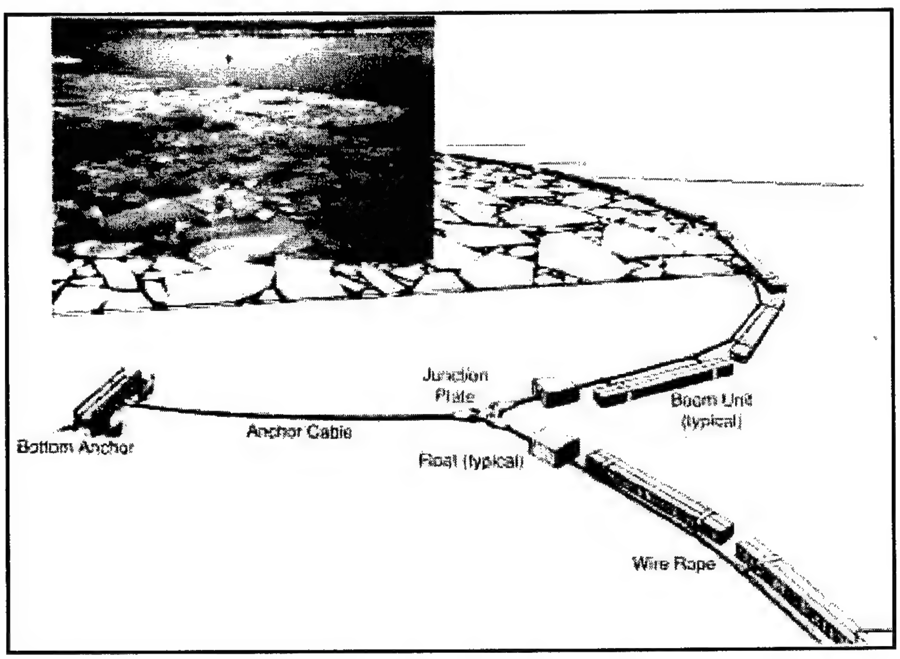


Figure 3-1. Typical ice boom arrangement.

a. Features of flexible structures. Flexible cable or wire rope structures are used to hold floating ice booms in place. The structures themselves are compliant but strong, and their ability to stretch or flex in response to the impact of moving ice sheets has prevented failure. They are used on generally accessible

bodies of water where one must control ice in winter while permitting unrestricted water use during the warm months. The ice cover that they help form and stabilize protects water intakes and navigation channels against excessive ice encroachment. The most important advantages of flexible structures are:

- The main structural components usually have a negligible effect on water flows.
- The structures (except for buried anchors) are readily installed prior to the ice season and removed afterward.
- The structures can withstand the passing of ice breakups.
- A variety of standardized components are available for a wide range of loads.
- The structures can be worked on using common maritime equipment, such as barges, cranes, winches, and tugs.

A list of flexible structures is given in Table 3-1.

b. Boom configuration. As shown in Figure 3-2, booms have been built in many configurations: some crossing the entire width, some with a gap to permit navigation, some restraining ice on only one side of the channel, and some more or less in the middle of a lake with open passage around both ends. The boom units are chained to wire rope boom cables, which connect to the shores or to midchannel anchor cables, usually at 30- to 122-meter (100- to 400-foot intervals), depending on the load. Until recently, the most common type of boom section was a 0.3- × 0.6- × 6-meter (1- × 2- × 20-foot) timber. The use of steel boom units of rectangular or circular cross section is gaining acceptance owing to reduced maintenance costs and improved performance compared to traditional timber booms.

c. Function. Boom structures can be installed across a portion of a river or across the entire width, according to the amount of control needed. The floating timbers intercept moving ice floes, frazil slush, and brash ice to form an unconsolidated ice cover upstream of the boom. Within 10 days the ice cover usually consolidates by the ice pieces freezing together. To be effective, an ice boom must restrain an ice cover at the surface without restricting water flow, and it must move up and down with the ice cover. An unconsolidated ice cover develops most rapidly when the water velocity (bringing ice floes to the boom) is as large as possible without causing appreciable quantities of ice to pass beneath the boom. Field tests showed that this velocity for a straight, 2.7-meter-deep (9-foot-deep) channel was 0.46 m/s (1.5 ft/s). This value is also optimum for the deeper but somewhat irregular Beauharnois Canal (located in Canada); the smooth ice cover that develops there allows efficient power generation in winter. In several major installations the mean velocities vary from 0.29 to 0.84 m/s (0.95 to 2.75 ft/s).

d. Site considerations. Locations where ice booms have been used successfully share common characteristics. The discharge is fairly constant and there are no abrupt changes in cross-sectional area. A boom can be used in fairly deep water, anywhere from 3 to 18 meters (10 to 60 feet) or more. Successful booms require a stable river bottom, i.e., one unaltered by sediment transport. If water velocities are too high, the ice floes can be drawn under the boom. A location that sustains a natural ice cover, even if only occasionally, is generally feasible. Accepted design criteria to achieve good boom performance are a Froude number, based on flow depth, no greater than 0.08, and a surface velocity no greater than 0.69 m/s (2.25 ft/s). Higher values indicate that ice thickening conditions may be present or that upstream progression of a retained ice accumulation may not be possible. At some sites, physical or numerical modeling may be necessary to select the optimum location.

Table 3-1. Flexible Ice Control Structures

Type of Structure	Figure No.	General Function*	Water Body	Material	Dimensions (m)	Span (m)	Force Level† (kN/m)	Water Depth (m)	Avg. Water Velocity (m/s)	Organization	Notes
Ice Booms Single timber		icfs, p	St. Lawrence River	Douglas fir	0.36×0.55×9	122	8.5^{m}	5–15	0.3–0.8	Ontario Hydro, Cornwall & Toronto Ontario; PASNY, Massena, New York	
	3-3c	icfs, p	Lake Erie	Douglas fir	0.36×0.55×9	122	20^{d}	5.5	0.45	Ontario Hydro, Niagara Falls, Ontario; PASNY, Niagara Falls, New York	
	3-3c	icfs, n	Lake St. Peter	Douglas fir	0.36×0.55×9	122	9.3^{m}	3	0.3	Transport Canada, Marine Services, Montreal	
	3-1	icfs, n	St. Marys R.	Douglas fir	0.3×0.6×6	62.5	10.6^{m}	3–10	0.8	Detroit District, U.S. Army Corps of Engineers	76-m-wide opening between boom ends for ship navigation
Double timber	3-3f	icfs, n, p icfs, ijr	Lake St. Francis Oil Creek	Douglas fir & steel Douglas fir & steel	0.36×0.55×9 0.83×0.83×20; 0.67×0.67×16	122 38	Unknown 6.7^{m}	8 0.6	0.75 0.50	Hydro Quebec, Montreal CRREL and Oil City, Pennsylvania	
Single pontoon	3-3a	icfs, ijr	Des Prairies R.	Hollow steel	0.4×0.8×6	68.5	44^{e}	4.5	0.5–0.85	Hydro Quebec, Montreal	
	3-3a, 3-5	icfs, n, p	Lake St. Francis	Hollow steel	0.4×0.8×6	61	16^{d}	6	0.43	Seaway Transport Canada, St. Lambert, Quebec	
	3-6	icfs	Allegheny R.	Steel; filled with foam	0.4×0.8×6	76	16.4^{d}	1.6	0.35	Pittsburgh District, U.S. Army Corps of Engineers	
Double pontoon	3-3g	icfs, n, p	Beauharnois Canal	Hollow steel pontoon; steel frame	0.9 (diam.) ×6; parallel pontoons, 1.8 on center	36	46.7^{m}	10.4	0.73	Hydro Quebec, Montreal	Maximum ice force measured
Single timber (direct load)		icfs, t, p	St. Marys R.	Timbers	Miscellaneous	21.3	Unknown	3.4	0.58	Edison Sault Electric Co., Sault Ste. Marie, Michigan	Timbers connected end to end
Rope	3-3e	icfs, x	St. Lawrence R.	Nylon & polypropylene braided rope	0.18 (diam.) ×91	81	Unknown	6.7	0.6–0.75 1.2–1.8	St. Lawrence Ship Channel Division Ministry of Transport, St. Lambert, Quebec	
Plastic pipe	3-3d 3-16	icfs, p	Pasvik R.	Plastic pipe; steel wire rope	0.3 (diam.)	Unknown	Unknown	Unknown	Unknown	Power Plant, Hestefoss, Norway	
Shear booms	3-3i	t, d	Missouri R.	Steel pipe; wood planks	1.1–1.35 (diam.) ×24	122	Unknown	~9	71.8	Montana Power Co., Great Falls, Montana	
	3-3h	t, d	New Clayton Lake	Steel pipes; wood planks	0.33–0.5 (diam.) ×7.3	216	Unknown	36.5	Unknown	Appalachian Electric Power Co. Clayton Development, Virginia	
Scow boom and weir		icfs	St. Lawrence R.	Scow; stone weir	1.4 (avg scow depth); 2.5 (height of weir)	~238	Unknown	~3.6	3–4.5		Boom can pass ice during high flows
Timber boom and weir		icfs	Chaudiere R.	Wood timbers; steel cable; concrete pier	1.5 (height of weir) 1.2 (height of boom)	42.9	14.6^{d}	≤3.5	≤2.6	Quebec Ministry of Natural Resources	
Frazil collector lines	3-8	icfs, x	Ottauquechee R.	Braided nylon line	15 (lengths of lines); 0.15 (spacing between lines); 98% open	5	$0.005–0.008^{s}$	0.3–0.5	0.7–1.1	CRREL	0.1-m spacing recommended
Fence boom	3-10 3-11	icfs, ijr, x	Mascoma R.	Wood 2 × 4s; wire rope	1.2 (height); 0.1 (gaps); 70% open	16.5	11.7^{d}	0.4–0.5	0.43	CRREL	

*icfs = ice cover formation and stabilization
d = shear or diversion
t = trash collection or diversion
ijr = ice jam reduction

x = experimental
p = hydroelectric power
n = navigation

†m = measured
d = design criterion
e = estimated from damage
s = shear drag coefficient
kips = kilo pounds of force

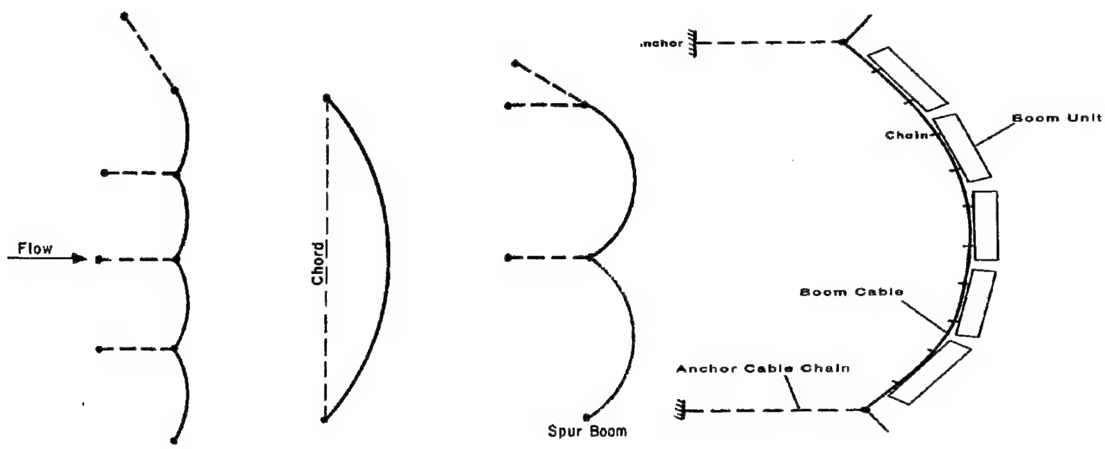


Figure 3-2. Ice boom configurations

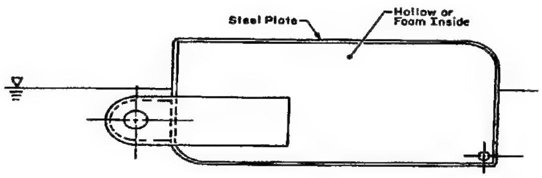
e. Boom components. Although ice booms vary in function and appearance, their wire rope structures are similar. The boom cables are longer than the spacing between the anchors, giving each boom span a sag configuration. In existing structures, boom cable length exceeds the span length by values ranging from 6 to 25 percent, corresponding to *sag ratios* (maximum offset of cable from the span divided by the span length) of 0.15 to 0.30. The greater the cable length is, the lower the tension in the cable is, but sag ratios in excess of about 0.20 excessively increase material quantities and cost.

(1) Individual wire ropes are connected by steel junction plates that are supported by buoys or floats. Galvanized wire ropes are often used for longer life, although the strength of the galvanized wire is 10 percent less than that of uncoated wire when new.

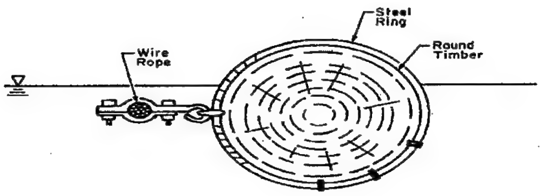
(2) Figure 3-3 shows a variety of ice boom designs. Designs h, i, and k have been used as shear booms for waterborne trash and logs; the floating material is expected to slide along the upstream face of the boom. The proper combination of buoyancy and stability can be determined through tests and analysis. Wooden timbers can lose effectiveness by becoming waterlogged, another factor prompting the current transition to steel boom units.

(3) Anchor types for ice booms vary, depending on the type of riverbed and bank materials. Depending on width, a structure that reaches from shore to shore will have anchors onshore and midstream anchors along the river bottom. Midstream anchor lines from the river bottom to the floating parts are generally about 12 times longer than the water depth. Typical anchors are shown in Figure 3-4. The cell structure is sometimes used at the midstream end of a spur boom, which reaches only part way across a river.

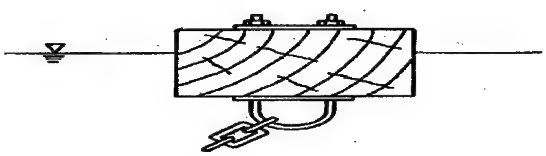
f. Examples of flexible booms (Perham 1983). An example of river ice control using an ice boom is found on the St. Marys River at Sault Ste. Marie, Michigan. Soo Harbor covers a large area, and immediately downstream from the harbor is a 183-meter-wide (600-foot-wide) man-made navigation channel called Little Rapids Cut. Below the cut lies Lake Nicolet, with its low velocity flows. The channel is dredged to a minimum depth of 8.2 meters (27 feet), and ocean-going vessels and lake carriers of various sizes up to 1000 feet (305 meters) long use it. Ice broken from Soo Harbor by passing ships would accumulate in Little Rapids Cut, so much so that at times the river discharge was retarded and



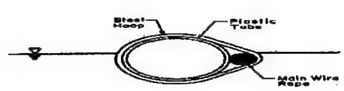
a. **Rectangular pontoon boom**



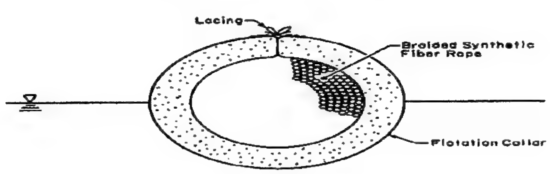
b. **Round timber boom**



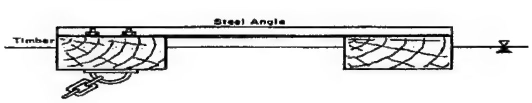
c. **Single rectangular timber boom**



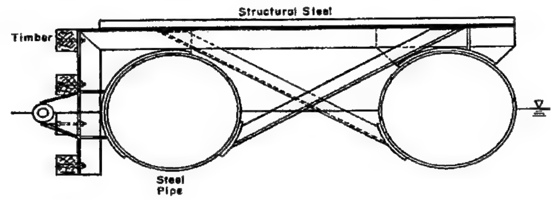
d. **Plastic tube boom**



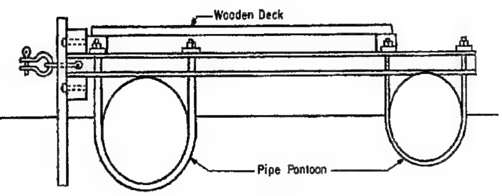
e. **Synthetic fiber rope boom**



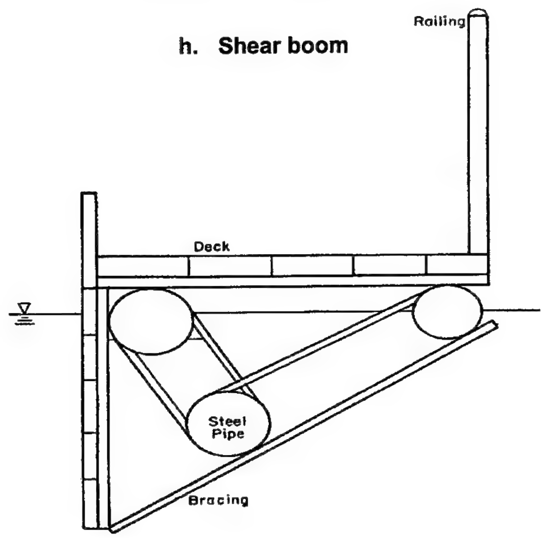
f. **Double rectangular timber boom**



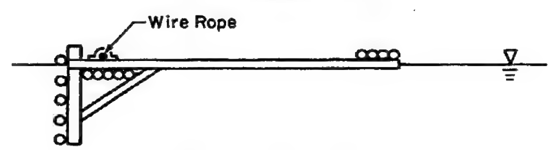
g. **Double steel pontoon boom**



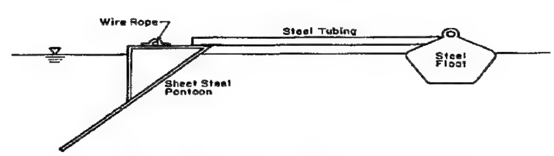
h. **Shear boom**



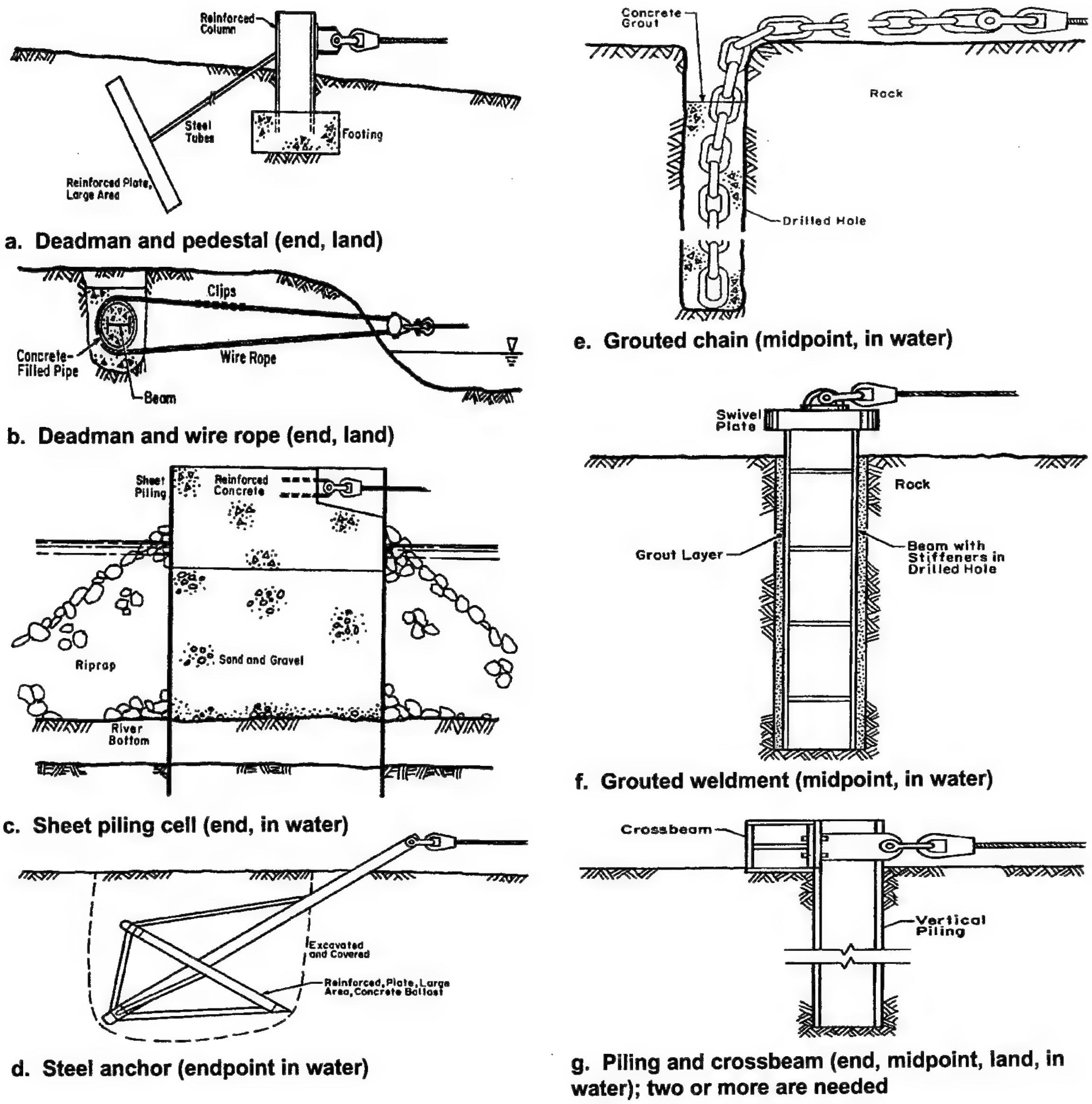
i. **Shear boom**



j. **Wooden pole boom**



k. **Triangular-skirted pontoon boom**



a. Deadman and pedestal (end, land)

b. Deadman and wire rope (end, land)

c. Sheet piling cell (end, in water)

d. Steel anchor (endpoint in water)

e. Grouted chain (midpoint, in water)

f. Grouted weldment (midpoint, in water)

g. Piling and crossbeam (end, midpoint, land, in water); two or more are needed

Figure 3-3. Cross sections of ice boom timbers and pontoons for a variety of ice boom designs

Figure 3-4. Typical ice boom anchors

unacceptably high water levels would develop in the harbor. Also ferry traffic to an island community was frequently disrupted.

(1) An ice–hydraulic–navigation model study of Soo Harbor and Little Rapids Cut determined the optimum location, orientation, and size for a floating ice boom. A boom with a 76-meter-wide (250-foot-wide) navigation opening was designed, built, and installed in 1975 at the upstream end of Little Rapids Cut. Later, two gravity structures (see paragraph 3-3*c*) were placed upstream of the boom to inhibit some troublesome lateral movement of the ice sheet along the western shore. The booms and the structures were

removed in the spring and reinstalled in the fall. Artificial islands eventually replaced the gravity structures (see paragraph 3-3*d*). This work was done as part of a now-completed demonstration program; the booms continue to be used because they provide stability to the ice cover during storms and intermittent ship transits, and they minimize ice interference with the ferry (Perham 1985).

(2) One of the largest booms to be installed in recent times (1981) is 2380 meters (7800 feet) long and located in Lake St. Francis upstream of the Beauharnois Canal in Canada (Figure 3-5). It was designed to accommodate ship navigation and was extensively tested as a model. The Lake Erie–Niagara River boom, although older, is 2680 meters (8800 feet long).

(3) A boom of similar construction was built in 1982 on the Allegheny River upstream of its confluence with Oil Creek at Oil City, Pennsylvania (Figure 3-6). Oil City has a long history of ice jams and floods that were caused by large deposits of frazil ice downstream of the confluence in a deep section of the river. The accumulations especially restrict flows from ice breakup on Oil Creek, which precedes ice breakup on the Allegheny River. The ice cover upstream of the boom typically stabilizes in early winter, reducing the frazil ice supply to the freezeup jam below the Oil Creek confluence.

(4) The 2680-meter-long (8800-foot-long) Lake Erie–Niagara River ice boom, located at the head of the Niagara River at the east end of Lake Erie, promotes ice arching and decreases the frequency and severity of lake ice runs into the Upper Niagara River. Retention of Lake Erie ice reduces the frequency of ice jams and ice blockages of hydroelectric intakes upstream of Niagara Falls. In 1997, the original timber pontoons were replaced with steel pipe boom units. This change is expected to increase the ice retention capacity of the boom and reduce maintenance costs.

g. Boom design considerations. There are a number of loads and other actions that must be considered when designing an ice boom (Foltyn and Tuthill 1996). Fluctuations in water level may allow the boom to pound on the bottom if it is too close to shore. Because of the resulting damage, this should be avoided. Generally, the amount of ice that will bleed through a small gap between the end of the boom and shore is negligible. The total force on the ice boom is

$$F_i = f_w \pm f_a + f_g + f_p + f_k - f_s \pm f_v \tag{3-1}$$

where

f_w = water drag force on ice cover

f_a = wind drag force on ice cover

f_g = gravity force

f_p = water flow pressure at beginning of ice cover

f_k = impact forces from collecting ice floes

f_s = shear force between ice and shore

f_v = forces resulting from vessel–ice–structure interaction.

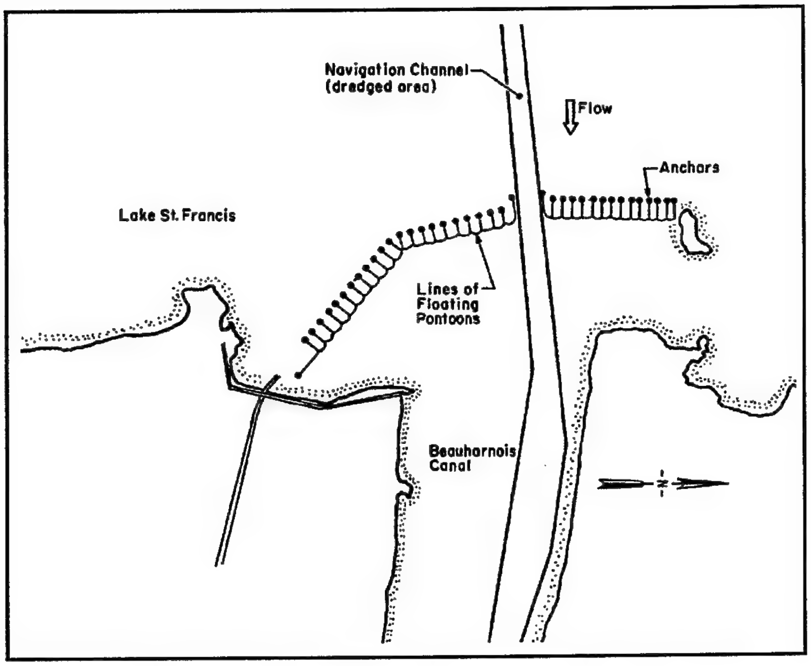


Figure 3-5. Plan view of the Lake St. Francis ice boom built in 1981

Most of these are self-explanatory or will be explained more fully in the example problem. The shear force between the ice and shore f_s is currently indeterminate, but field observations have shown that ice loads attributable to an unconsolidated ice cover come from the area upstream of the boom that measures four or five times the river width in length. In other words the drag forces on the ice cover in excess of four or five B (the river width) are taken by the shore and are not felt by the boom. Boom unit stability should be considered, as well as the maximum ice restraint capacity of the boom unit.

(1) The restraint characteristics of a generally applicable timber configuration are given in Figure 3-7. The timber has a no-load submergence of 0.75 and a connection point upstream on the bottom. The curves show that the ice restraint force will be about the same for anchors pulling horizontally and anchors pulling downward at a small angle $\alpha = \tan^{-1} 0.08$ until the tilt β of the timber is about 35 degrees. At 35 degrees, the $\alpha = 0$ curve changes slope rapidly and diverges from the $\alpha = \tan^{-1} 0.08$ curve. The physical problem here is that, as the tilt angle nears 40 to 45 degrees, the ice can slide over the timber; this tends to make this portion of the curves unreliable. The restraint capacity of a boom timber increases by the cube of the timber width.

(2) The override effect can be and is used for rectangular boom-unit cross section as a protective measure that helps the boom survive the high loads imposed at breakup. Generally, the rectangular-section timber booms have a load capacity ranging from 74 kg/m (50 lb/ft) to 298 kg/m (200 lb/ft), depending upon boom design and ice type. There are double pontoons that have load capacity of over 744 kg/m (500 lb/ft) for rectangular boom-unit sections. The overtopping resistance of the 0.76-meter-diameter (2.5-foot-diameter) circular-section boom units on Lake Erie is approximately 1120 kg/m (750 lb/ft), four times greater than the maximum ice resistance of the original timber boom units. The load capacity depends on the buoyancy, the righting couple or moment, and the anchor location.

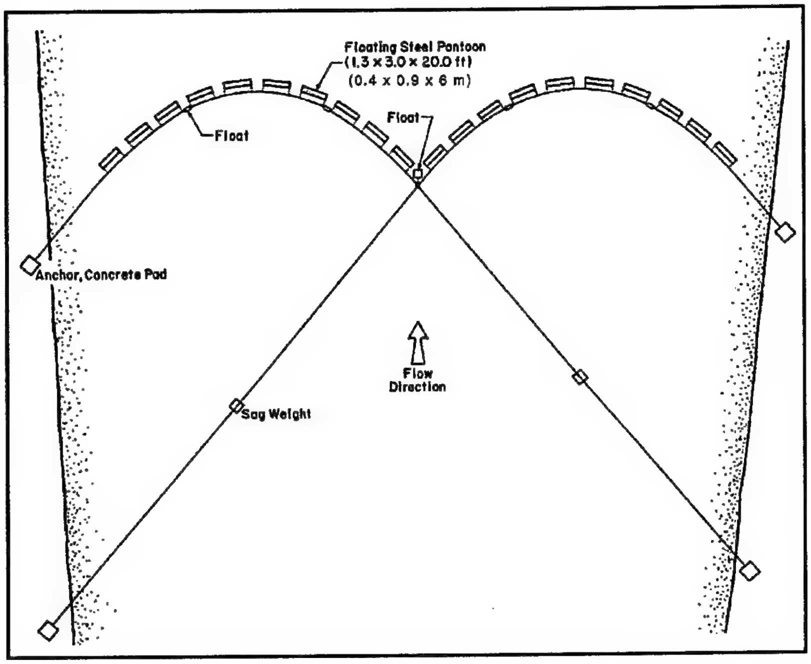


Figure 3-6. Plan view of the Allegheny River ice boom built in 1982

(3) A failure analysis should be made of the multicomponent structure to estimate the increased loads exerted on members adjacent to a component that fails. The structure also should be evaluated for its response to a solid ice sheet that only acts at one or two locations along the boom, and to an ice sheet that starts moving while frozen to the floating timbers. The calculated forces in these cases could be extremely high. Under such circumstances the load increase may not be distributed uniformly to the anchor points.

h. Example problem of ice boom design. This example is based on a power canal 3.2 kilometers (2 miles long) and 3.0 meters (10 feet) deep with a 7.6-centimeter-thick (0.25-foot-thick) ice cover. It is 54.9 meters (180 feet) wide at the bottom and 61.0 meters (200 feet) wide on the top. The hydraulic slope with an ice cover is 3.81×10^{-4}. The canal is essentially straight and aligned with the prevailing winds which can reach 27.7 m/s (91 ft/s) at 9.1 meters (30 feet) above the surface. The bottom has a Manning's roughness coefficient of 0.032 and a Froude number of 0.11, which is higher than desired. The initial ice cover roughness coefficient is 0.05. The composite roughness coefficient is 0.041, determined using Equation 4-2. Equation 3-1 above has a number of unknowns to be determined:

$$f_w = \gamma_w R_i S (5B) \tag{3-2}$$

where

γ_w = specific weight of water = 62.4 lb/ft^3 (1000 kg/m^3)

R_i = hydraulic radius influenced by the ice, assumed at 5 feet (1.5 meters)

S = uniform flow slope

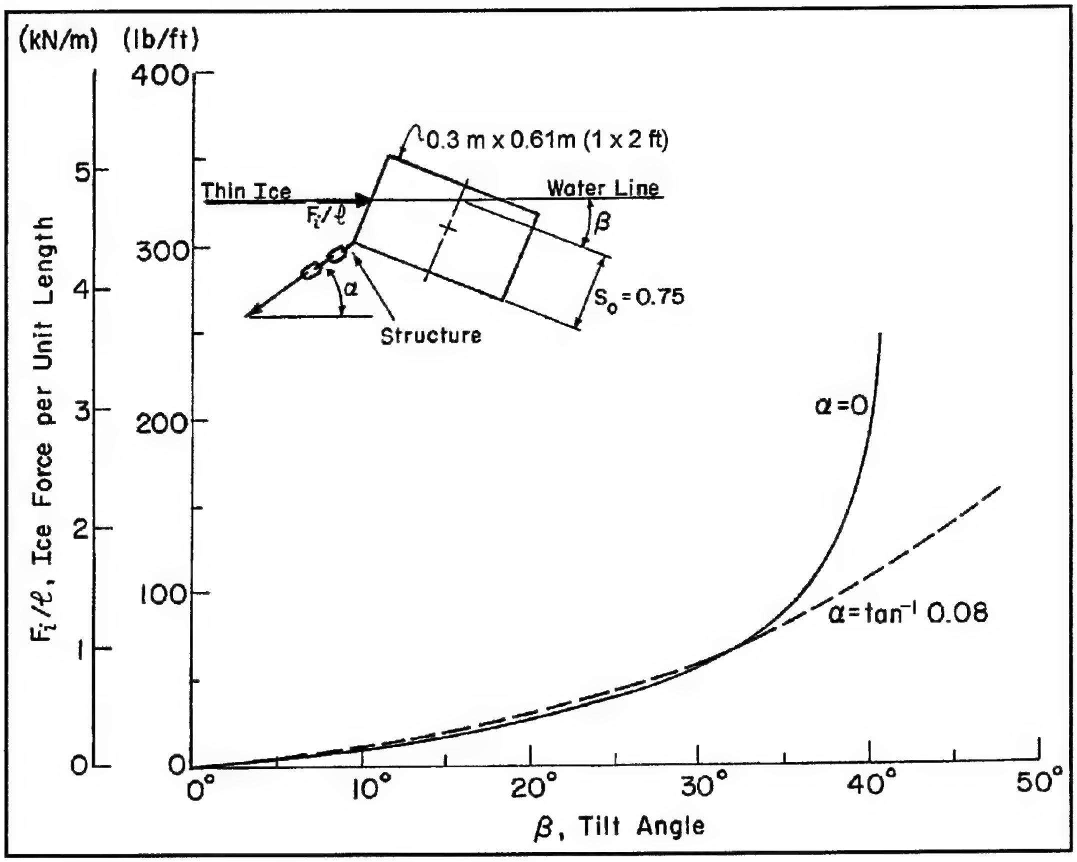


Figure 3-7. Ice restraint for a 0.3- × 6.1-meter (1- × 20-foot) boom timber for the conditions indicated

B = channel width

$f_w = 62.4 \times 5 \times 3.81 \times 10^{-4} \times 5 \times 200 = 119$ lb/ft (177 kg/m)

$$f_a = c\ \rho_a\ U^2\ 5B \tag{3-3}$$

where

c = drag coefficient, which can vary between 1.7×10^{-3} and 2.2×10^{-3}

ρ_a = air density, kg/m^3 (lb/ft^3)

U = mean wind speed at the 30-foot (9.1-meter) height, ft/s (m/s)

$f_a = 2.2 \times 10^{-3} \times 0.00257 \times (91)^2 \times 5 \times 200 = 70$ kg/m (47 lb/ft)

$$f_g = \gamma_i\ \ 5B\ h\ S \tag{3-4}$$

where

γ_i = specific weight of ice = 918 kg/m^3 (57.3 lb/ft^3)

h = ice thickness = 0.076 meters (0.25 feet)

$f_g = 57.3 \times 5 \times 200 \times 0.25 \times 3.81 \times 10^{-4} = 8.2$ kg/m (5.5 lb/ft).

The values of f_p and f_k are considered negligible. The value of f_s is taken into account by using $5B$ and f_v is not considered in this case. So, repeating Equation 3-1,

$$F_i = f_w \pm f_a + f_g + f_p + f_k - f_s \pm f_v$$

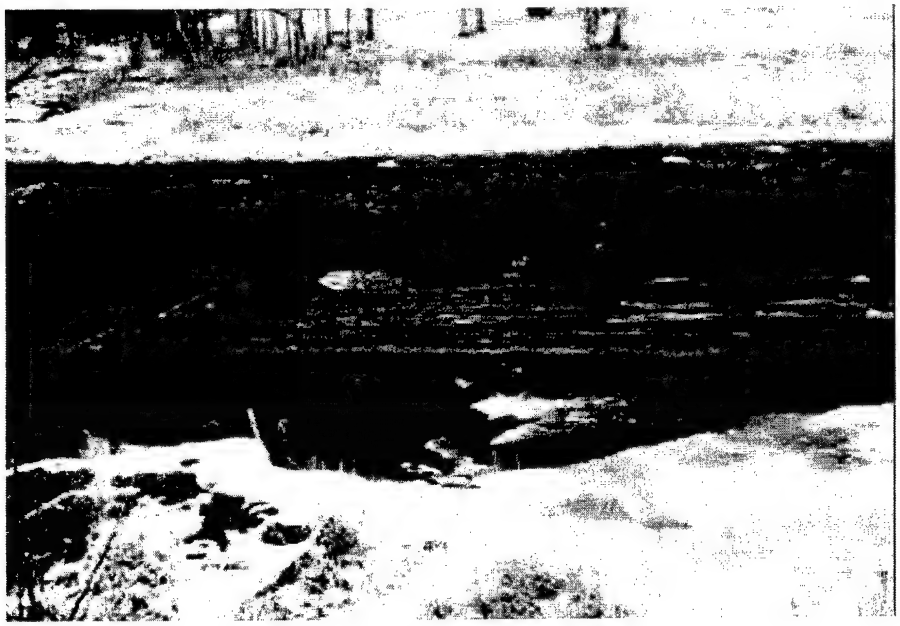
$$F_i = 119 + 47 + 5.5 + 0 + 0 - 0 \pm 0 = 255.7 \text{ kg/m } 171.5 \text{ lb/ft.}$$

That is 255.7 kilogram-force per lineal meter (171.5 pounds-force per lineal foot) of boom, assuming the wind is blowing downstream. For calculating the tension in the boom cables, see Foltyn and Tuthill (1996).

i. Other flexible structures. Two other types of flexible structures may be described, frazil collector lines and fence booms. Both of these concepts were examined experimentally in the 1970s and early 1980s, but only the fence booms have received additional study and development in more recent years. Similar in concept to frazil collector lines, frazil nets have been used to promote ice cover formation upstream of hydroelectric dams in Sweden.

(1) Frazil collector lines, or line arrays, are made from nylon, polypropylene, polyester, or wire rope. An array is anchored in a stream, and active frazil ice freezes to each line (Figure 3-8a). Overnight accumulations 10 to 13 centimeters (4 to 5 inches) in diameter on each line are common. As the lines and frazil ice float on the stream's surface, the entrapped interstitial water is practically stationary and freezes quickly to form an ice cover over the entire line array (Figure 3-8b); even 0.64- and 0.79-centimeter-diameter (1/4- and 5/16-inch-diameter) wire ropes are buoyed up by the frazil ice accumulations. In concept, covering a troublesome open-water reach of a canal or stream with one or several sets of steel or synthetic fiber lines seems feasible. The ideal combination of unit length and frequency of units needed to prohibit further supercooling was never determined. If the lines are naturally buoyant, an array can be anchored where it will freeze into the ice sheet without being buoyed by frazil ice; it would then become a reinforcement and a means for supplemental restraint. Arrays of buoyant lines could also be used to stabilize existing large ice sheets by holding them in place against flow forces after they crack free from shore. The idea would be for the lines to expand the area that a buoy, or a timber, might be expected to reliably influence. An example is shown in Figure 3-9. Such cracks can result from water level changes, ship passages, or warm water discharges. Also, several sets, probably without the shore anchors shown in Figure 3-9, have the potential for delaying spring ice movement on a section of river. The loss of a line array during ice breakup would be a possibility, and the consequences of this loss must be considered.

(2) A fence boom is a structure supported across a stream by steel cables and resting on the streambed (Figure 3-10). The fence boom has little effect on streamflow before icing conditions start. Its appearance is that of a slatted snow fence or a wooden grate. It is stable when connected to single anchor points buried in each bank because of the curved shape it takes in response to the hydrodynamic and static water pressures acting on it. Active frazil ice generated in the stream attaches to the vertical



a. Array of lines, 4.9 × 15.2 meters (16 × 50 feet)

b. Resulting ice cover

Figure 3-8. Frazil collector lines

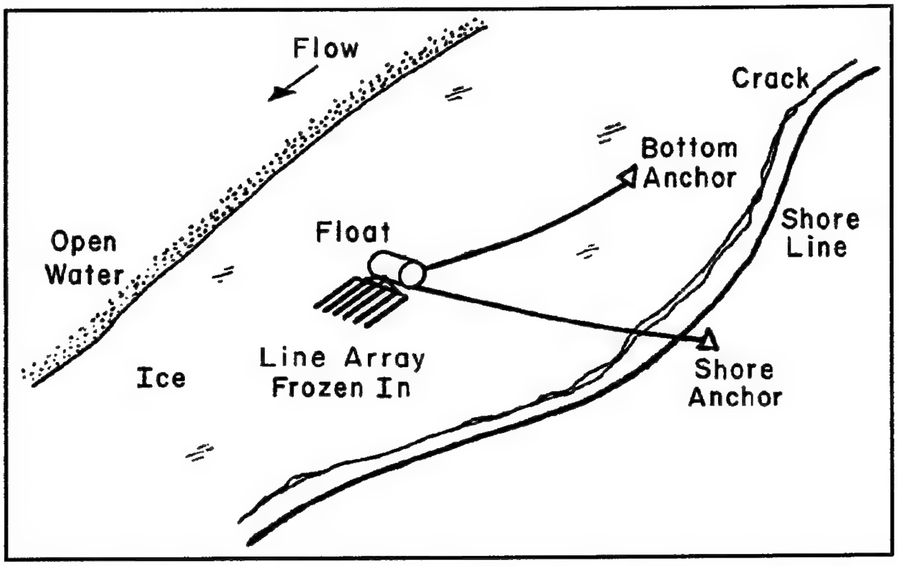


Figure 3-9. Line array anchoring an ice sheet that has cracked free from shore

Figure 3-10. Fence boom, 1.2 meters (4 feet) high, across the Mascoma River, New Hampshire

bars and eventually fills in the spaces between the bars from the streambed to the surface. Water flows continuously, so the frazil ice blockage causes the water level upstream of the boom to rise and overflow the blockage. This, in turn, increases the elevation of the region that can be blocked by frazil ice. Eventually, a pool is created upstream, with water flowing over the top of the fence boom (Figure 3-11). An ice cover develops and progresses upstream until a surface flow velocity of 0.69 m/s (2.25 ft/s) is reached. Field tests of the original fence boom were successful, but it was tested in only one small river.

Figure 3-11. Pool formed by the action of frazil ice on a fence boom

Streambed erosion was a problem, pointing to the need for bed protection. A similar free-standing fence boom is used to form an ice cover upstream of a small hydropower project in northern Japan.

3-3. Ice Control by Rigid or Semirigid Structures

Rigid or semirigid structures may or may not have moving parts. They are appreciably more rigid than a typical ice boom, but their deflection in response to the horizontal push of an ice sheet is on the same order as the deflections that develop in the ice sheet itself. Because these structures are generally unyielding, they are particularly susceptible to ice sheet impact and thermal expansion loads. The state of the art in design today is generally based on the conservative values of load and stress developed for dams and bridges. A list of rigid or semirigid structures is given in Table 3-2.

a. Pier-mounted booms. Boom elements attached to piers may be either movable (e.g., the Montreal ice-control structure) or fixed (e.g., the spillway barrier at the Sigalda Project in Iceland).

(1) The Montreal ice-control structure (Figure 3-12) was built primarily to compensate for the ice conditions caused by the narrowing of the St. Lawrence River because of construction of the Expo '67 World's Fair. The structure, which is permanent, originally used floating steel booms or stop logs set between concrete piers to collect ice floes and help stabilize an ice cover earlier in winter than would normally be the case. The booms were designed to move vertically in guide slots in the piers, kept ice-free by radiant electric heat. The 2.04-kilometer-long (1.27-mile-long) structure cost approximately $18 million in 1964–65. The operating levels for the booms were determined by model studies and analysis of the backwater effects from the formation of the ice cover downstream in Montreal Harbor and below. At these levels the large quantities of ice expected from the Lachine Rapids upstream can be stored beneath the ice cover. The structure was designed using dam technology to provide high structural integrity. The booms were designed to float, but they were not allowed to turn over as they might do with a flexible rope structure. In spite of their strength, they were susceptible to damage by the concentrated impact loads of moving ice sheets. Also, the operation of the structure has been affected by

Table 3-2. Rigid or Semirigid Ice Control Structures.

Type of Structure	*Figure No.*	*General Function**	*Water Body*	*Material*	*Dimensions (m)*	*Force Level† (kN/m)*	*Water Depth (m)*	*Avg. Water Velocity (m/s)*	*Organization*	*Notes*
Booms Floating (pier-mounted)	3-12	icfs, ijr	St. Lawrence River	Steel pontoons; concrete piers	1.7 × 1.8 × 25 (pontoons)	73^d (pontoons) 146 (piers)	6.7	≤1.8	Canadian Coast Guard, Ministry of Transport, Montreal	A few pontoons were broken by ice impact
Fixed	3-13	icr	Tungnaa R.	Reinforced concrete	5.5 (height w/flash boards) 2.5 × 110	146^d 3000 centerload	6–6.4	≤4.9	Landsvirkjun (National Power Co.), Reykjavik, Iceland	Reservoir overflow spillway
	3-14	ir, d	Tungnaa R.	Reinforced concrete	7.9 × 6.1 × 60	58^d	7–9	Unknown	Landsvirkjun (National Power Co.), Reykjavik, Iceland	Power canal inlet
Border ice bridge		icfs	Dvina R.	Ice	≤200	Unknown	deep	quiet	—	Reinforced with wire at times
Artificial islands Low	3-19b	icfs, n	St. Lawrence R.; Lake St. Peter	Stone; glacial till (0.6 - 1 m diam)	10.4 (diam. at water line); ~79 (diam. at base); 2.5 (height above LWL)	Unknown	2.7–5.2	0.3–0.5	Canadian Coast Guard, Ministry of Transport, Ottawa	
High	3-19a	icfs, n	St. Lawrence R.; Lake St. Peter	Stone; glacial till	10.9 (diam. at water line); ~74 (diam. at base); 4.3 (height above LWL)	Unknown	6.4–7.5	0.3–0.5	Canadian Coast Guard, Ministry of Transport, Ottawa	
	3-20	icfs, n	St. Lawrence R.; Lake St. Louis	Quarry stone; armor stone	Square: 11.9 (length of side at water line); 35 (length of side at base); 5.8 (height)	Unknown	4.4	Unknown	Seaway Transport Canada, Cornwall, Ontario	Undergoing evaluation
Light tower bases	3-22	icfs, n	St. Lawrence R.	Timber cribs & piles	Square: 7.6 (length of side)	1500^d	1.8	Unknown	Canadian Coast Guard, Ministry of Transport, Ottawa	Replacement for failed structure
	3-29	icfs, n	Lake St. Peter	Concrete & steel piles	Conical: 2.4 (diam. at top); 45° incline	$830\text{–}1040^d$	2.0	0.3–0.5	Canadian Coast Guard, Ministry of Transport, Ottawa	No failure
	3-30	n	Lake St. Clair	Steel shell & piles; concrete cap	5.5 (diam. at top); 11 (diam. at base)	790^d	5.5	~0	U.S. Coast Guard, Cleveland Ohio	
	3-31	n	Lake Erie	Steel	Square: 0.37 (length of side)	2800^d with 1.67 m ice	3.0	~0	U.S. Coast Guard, Cleveland, Ohio	
Groins	3-16	icfs, p	Pasvik R.	Stone	Unknown	Unknown	Unknown	Unknown	Water Resources & Electricity Board, Oslo, Norway	
	3-15	icfs, p	Burntwood R.	Stone; earth	9 (max.ht.); 274 (length); 0.9–1.2 (diam. of nose armor boulders)	Unknown	7	≤5.8	Manitoba Hydro, Winnipeg	Flow increased by river diversion; ice boom also used
Timber cribs	3-21	icr	Narraguagus R.	Timbers; stone	4.3 (length) × 2.4 (width) × 4.9 (height); 0.5 slope on face	73^d	2.3	0.3	New England Division, U.S. Army Corps of Engineers	Also 6.9-m-high weir; three cribs
Rock-filled scow	3-17	icr	St. Marys R.	Steel; stone	7.3 × 24.3	50^c	1.8	0.5	Detroit District, U.S. Army Corps of Engineers	Supplemental anchors
Crane weights		icr	St. Marys R.	Reinforced concrete	3.3 × 3.3 × 3.7; stack of six weights	58^c	1.8	0.5	Detroit District, U.S. Army Corps of Engineers	Supplemental to scow
Weirs	3-23	icfs	Small streams	Logs; steel	30–61 (pool length)	Hydrostatic pressure	1.5	Unknown	Bureau of Reclamation, Engineering & Research Center, Denver	
	3-24	icfs, x	Israel R.	Stone; gabion basket	2 (height) × 52 (length)	88 at crest	2.1	<0.1	New England Division, U.S. Army Corps of Engineers	Local protection project
Weir and grating	3-25	icfs	Chaudiere R.	Concrete piers; steel grill	12.8 (height) × 190 (length)	Unknown	8.2	Unknown	Quebec Ministry of Natural Resources, St. Georges, Quebec	

*icfs = ice cover formation and stabilization
ijr = ice jam reduction
icr = ice cover retention
ir = ice retention
d = shear or diversion
n = navigation
p = hydroelectric power
x = experimental
†d = design criterion
c = estimated

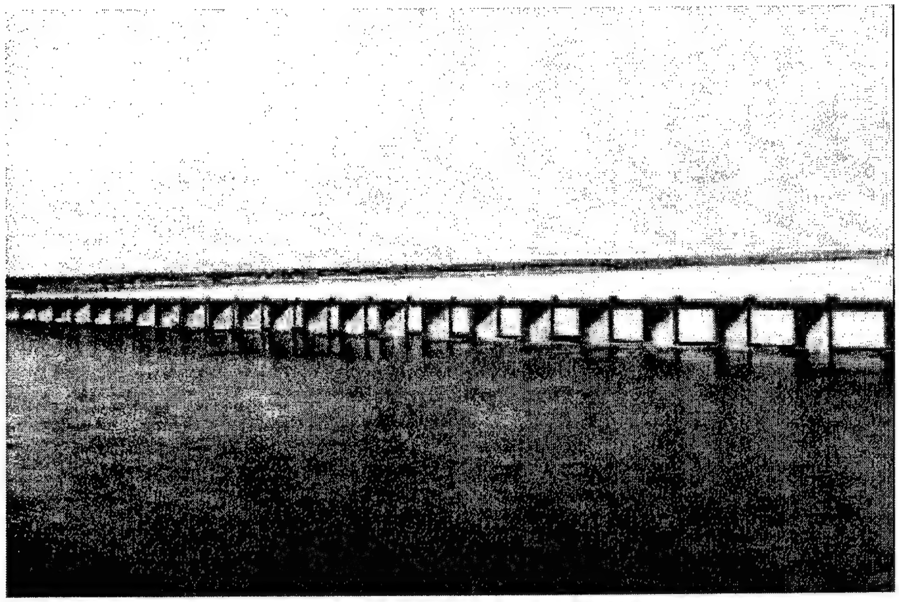


Figure 3-12. Montreal ice-control structure (looking southwest and upstream); LaPrairie Basin is in the background

the same hydraulic factors as the other booms. Owing to continued operational difficulty, the boom units were eventually removed. The piers alone were found to be adequate to form an upstream ice cover.

(2) Reinforced concrete beams of great depth are used at some reservoirs to restrain ice while water is being discharged over a spillway or into a canal. The spillway barrier shown in Figure 3-13 is located on the Sigalda power project reservoir on the Tungnaa River in Iceland, about 160 km (100 miles) east of Reykjavik. The space below it provides 4.9 meters (16 feet) of clearance. Ice remains naturally on the reservoir under all but the most severe flood conditions. The barrier is designed to retain ice during the latter low-frequency, high-discharge events. Three miles (4.8 kilometers) downstream of Sigalda, a boom protects the entrance to the power canal of the Hraunyjafoss power project. During periods of frazil ice generation, the frazil agglomerations collect at the reinforced concrete boom (Figure 3-14). The structure functions as a shear boom when a portion of the river flow is used to convey the frazil ice over an adjacent, gated sluiceway. Model studies showed that the deep, fixed boom would be more effective at keeping ice from the power canal than was a large (but relatively smaller) floating timber boom. Fixed structures such as these are useful where the water level changes little. If seiches are large or the operation of ships is an important consideration, then a fixed boom would probably not be appropriate.

b. Stone groins. A groin is usually a rigid structure built out from shore to protect it from erosion, to trap sediment, or to direct the flow. Groin arrangements have been used for ice control at the Manasan Falls control structure on the Burntwood River in northern Manitoba, Canada, and at Hestefoss on the upper Pasvik River in northern Norway. At both places there are groins opposite each other across the river, and the Pasvik system has additional groins. Both arrangements are supplemented by ice booms upstream of the groins.

(1) The Burntwood River was made part of the Churchill River Diversion, and its flows in winter were increased from 28 to 850 m^3/s (990 to 30,000 ft^3/s). Model studies indicated that frazil ice generation in the reach above Manasan Falls could lead to hanging dams, ice jams, and flooding in

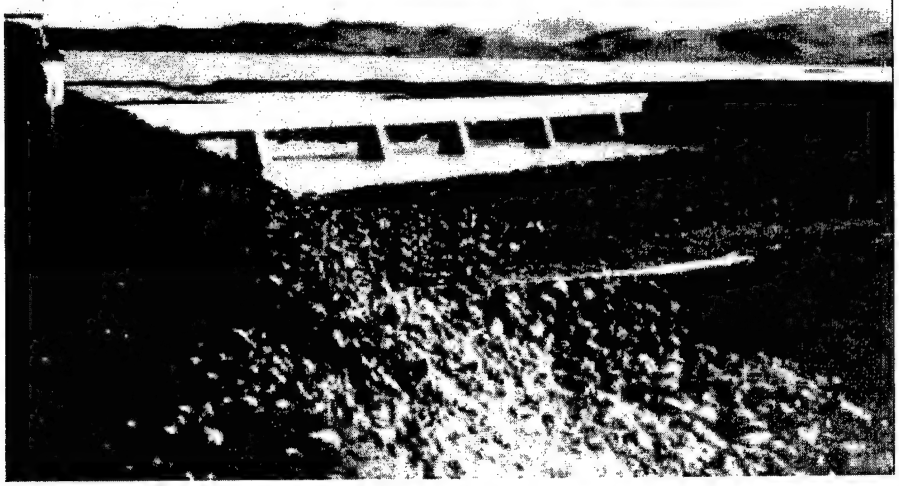


Figure 3-13. Fixed ice boom at Sigalda Reservoir, Tungnaa River, Iceland

Thompson, a city 6.4 kilometers (4 miles) downstream. The control structure at Manasan Falls was constructed to increase the upstream water levels sufficiently to promote the formation of a stable ice cover. It consists of two rock-filled groins creating a trapezoidal opening (Figure 3-15). The two groins have upstream filters and seals, and the ends of the groins were protected by 0.9- to 1.2-meter-diameter (3- to 4-foot-diameter) armor rockfill. The armoring material has remained stable at flows up to 850 m^3/s (30,000 ft^3/s) and at average water velocities in the gap exceeding 5.8 m/s (19 ft/s). The channel constriction provides the required stage and velocity conditions for upstream ice cover formation behind a boom. A larger hydroelectric dam planned for a nearby site will provide the ultimate solution to the problem.

(2) On the Pasvik River, a substantial amount of frazil and anchor ice is formed in the reach above the powerhouse at Hestefoss. Natural anchor ice dams as high as 3 meters (10 feet) can form, but they are poorly anchored to the riverbed and can break, causing heavy ice and transient water flows. The river was made narrower in the rapids area by installing stone groins to promote ice bridging and to stabilize the ice dams (Figure 3-16). To reduce the surface area of open water and the amount of anchor ice, timber booms were installed above the rapids and a plastic pipe boom was installed below the rapids in the forebay of the powerhouse. In 1970, after 2 years of observations, the stone groins were functioning as expected.

(3) The technology for groins is described in shore protection manuals. The applications described for ice are not as simple as they seem, but groins may be the least expensive and most reliable method of ice control at a particular site.

c. Removable gravity structures. A problem developed with the St. Marys River ice-control boom in the harbor at Sault Ste. Marie, Michigan, because the ice cover above the west arm of the boom would break free from shore and move laterally into the open ship track. Although the loads from the ice sheet were within the expected range, their distribution was different enough to cause damage when the boom timbers were frozen solidly into the ice cover. Damage could be prevented if the ice cover could be kept

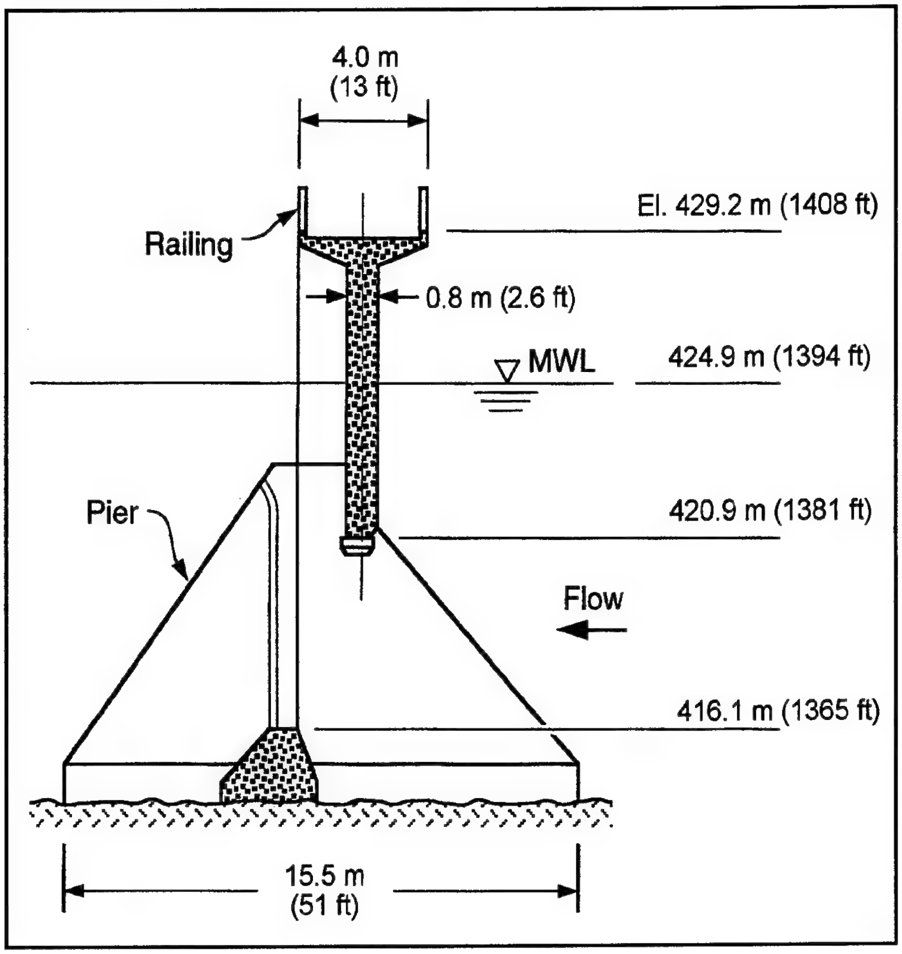


Figure 3-14. Inlet structure at Hraunyjafoss Power Canal, Tungnaa River, Canada

from rotating. The only method that could be used at that time was a removable gravity structure. The main structure used was a scow, surcharged to a total weight of 2.45×10^5 kilograms (270 tons) and sunk in shallow water (Figure 3-17). The scow was also secured with ship anchors. In the spring it was refloated and moved away. The method has worked very well.

(1) Later, observers noticed that sewage plant effluents weakened part of this ice cover on the St. Marys River. Thus, the ice-holding capability of the scow was supplemented by placing a stack of crane weights in the shallow water of Soo Harbor, about halfway between the scow and the ice boom. The reinforced concrete crane weights key together when stacked and are bound into a unit by wire ropes. The six crane weights weigh a total of 8.6×10^4 kilograms (95 tons). They helped to reduce the rotating ice sheet problem to a manageable level.

(2) The holding force available from gravity devices depends not only on the weight of the device in water but also on the coefficient of friction between the device and the bottom; a value of 0.3 was used in the Soo Harbor analysis. The force level was estimated from the expected action of water and wind drag

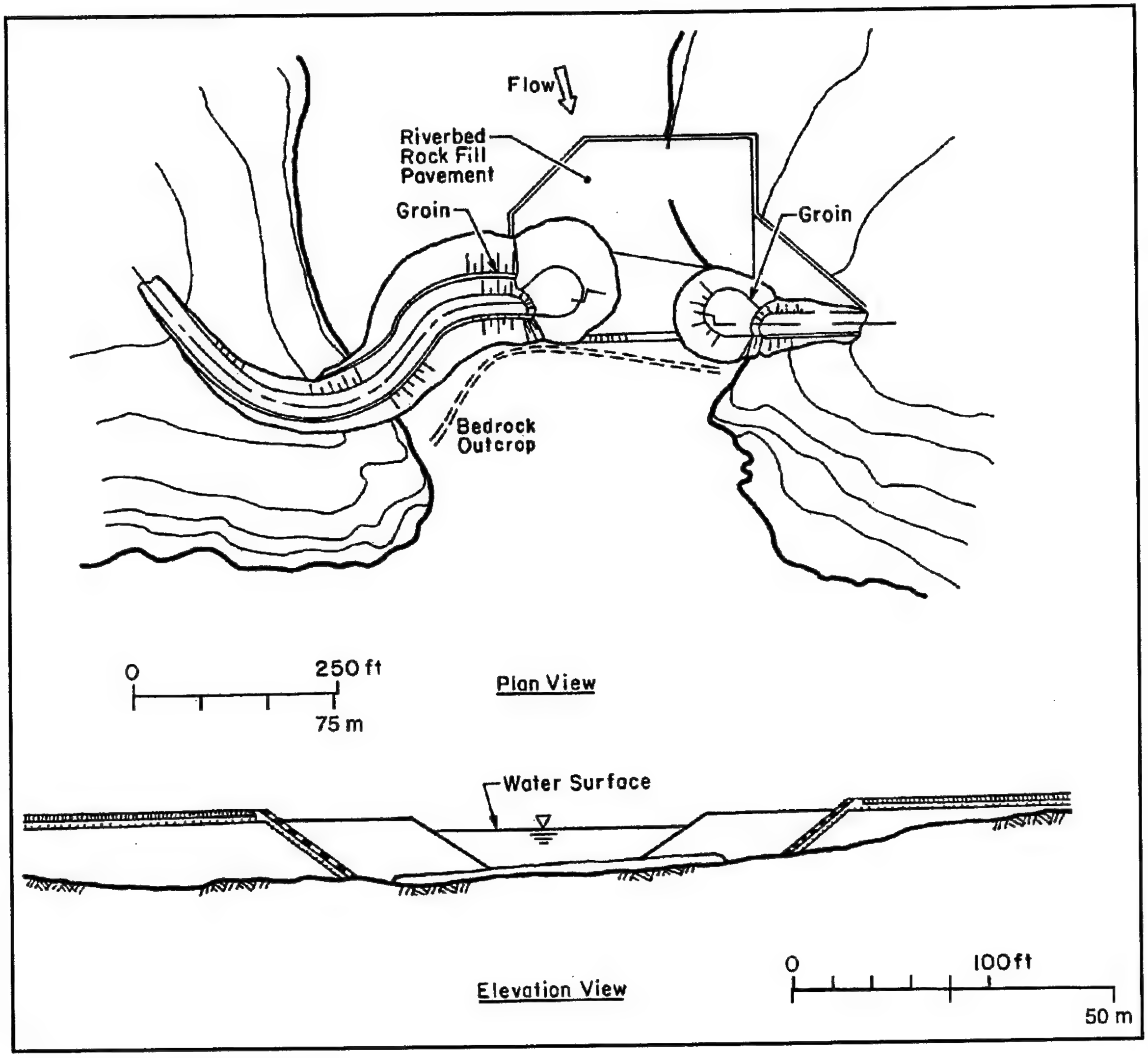


Figure 3-15. Ice-control groins and booms on the Burntwood River, Manitoba, Canada

on the maximum expected ice sheet. Eventually, all the removable devices in Soo Harbor were replaced by artificial islands.

d. Artificial islands. In the same manner that natural islands help hold ice in place, artificial islands can be used to help form, stabilize, and retain an ice cover in certain locations. One example is the Lake St. Peter section of the St. Lawrence River, about 80 kilometers (50 miles) downstream of Montreal, Canada (Figure 3-18). Lake St. Peter is about 13 kilometers (8 miles) wide and 32 kilometers (20 miles) long and has an average depth of 3 meters (10 feet). Passing through the middle of the lake is a 244-meter-wide (800-foot-wide) navigation channel dredged to a depth of 10.7 meters (35 feet). The water flow velocity in most of the lake averages about 0.3 m/s (1.0 ft/s), while in the channel it is 0.5 m/s (1.6 ft/s).

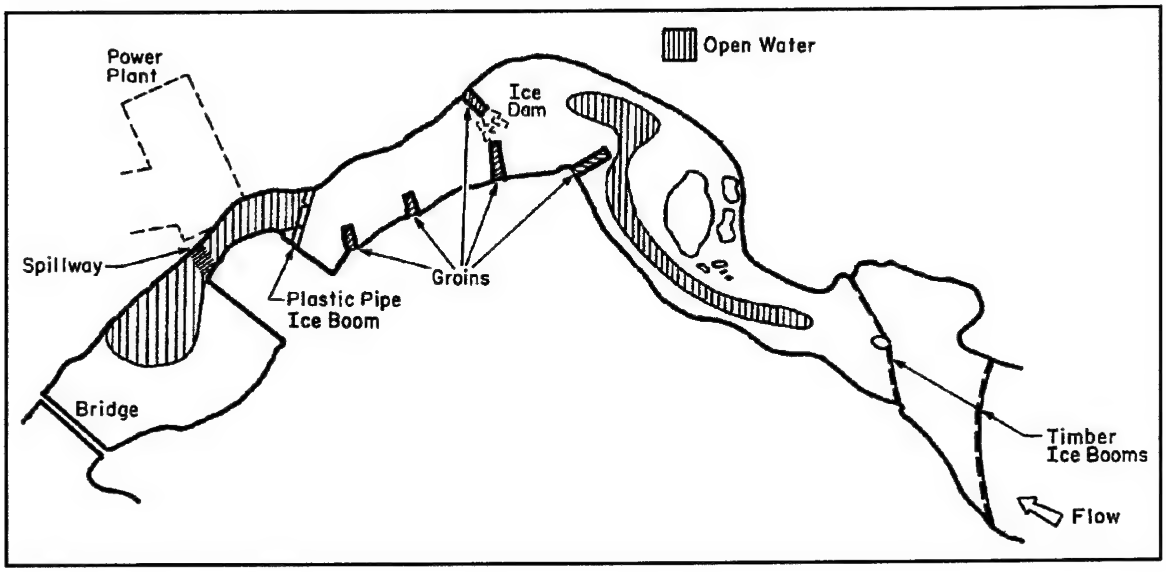


Figure 3-16. Ice-control groins and booms on the Pasvik River, Hestefoss, Norway (showing the maximum ice conditions) early March)

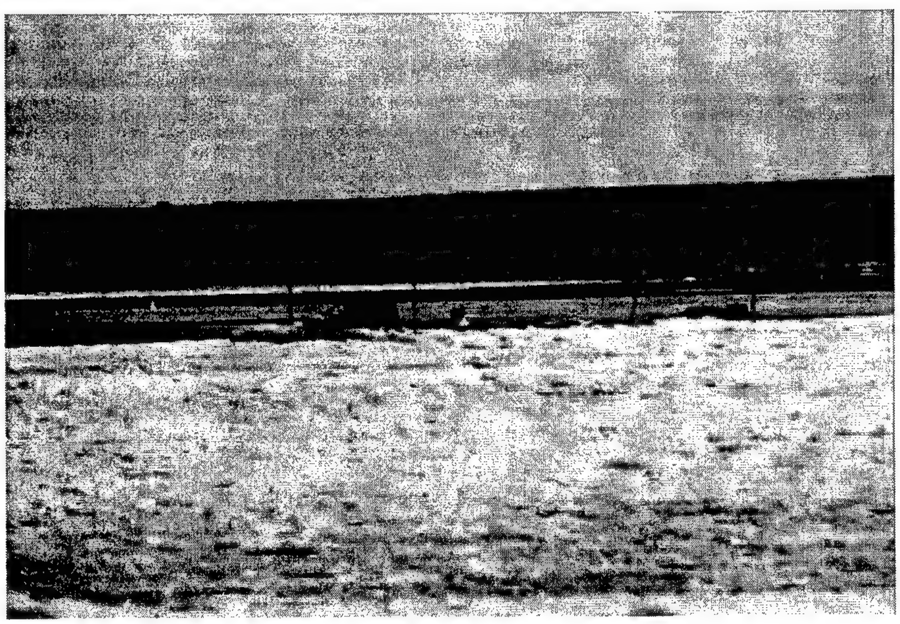


Figure 3-17. Rock-filled scow stabilizing the ice cover is Soo Harbor, Michigan

(1) To prevent floods in Montreal Harbor, a passageway for ice floes, slush, and frazil ice is maintained by icebreakers from Montreal Harbor to Quebec City. At times, however, ice sheets would break free and be moved by wind and water to clog the passageway. Occasionally, a strong northeast wind would move the floating ice back upstream. Some light-tower bases helped hold the ice, but more stabilization was needed.

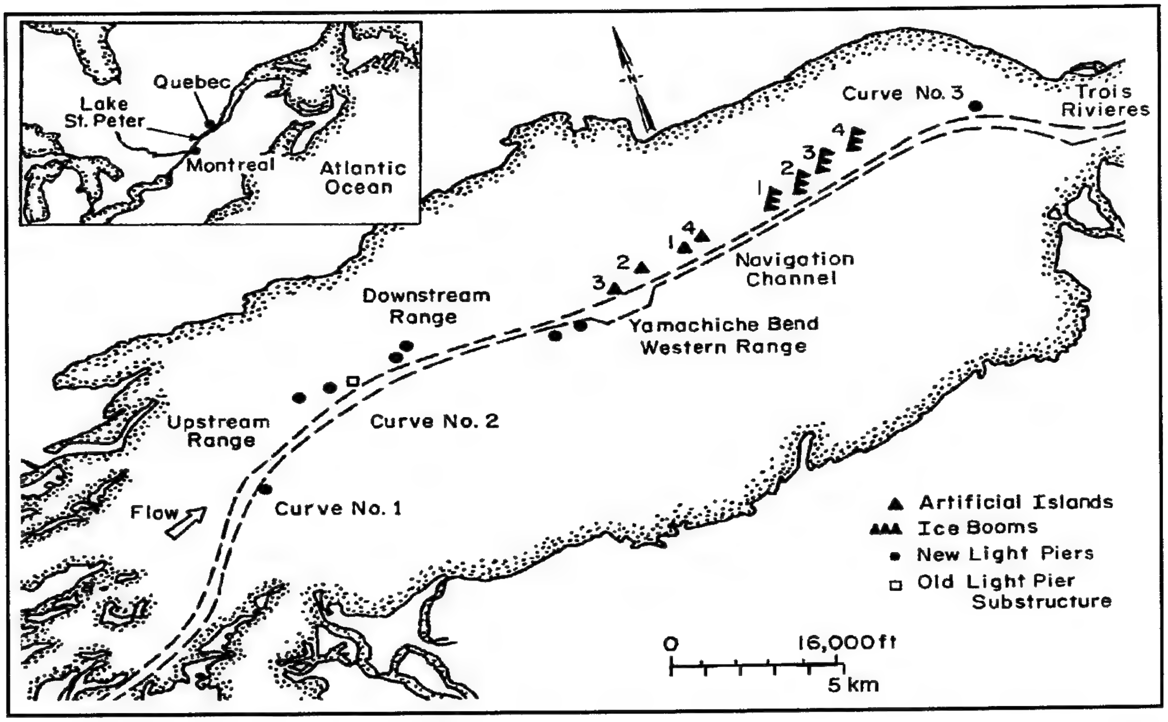


Figure 3-18. General plan and location of artificial islands, ice booms, and light pier in Lake St. Peter, St. Lawrence River

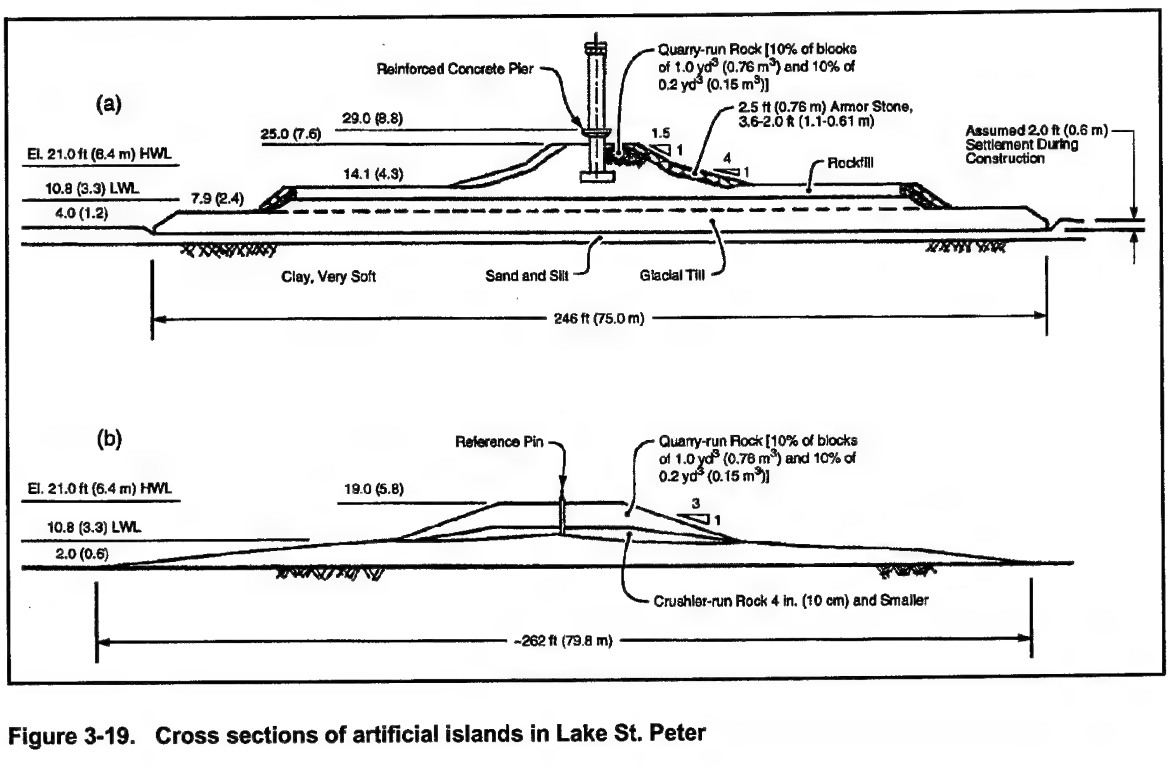


Figure 3-19. Cross sections of artificial islands in Lake St. Peter

(2) Several ice-control structures were evaluated in various parts of Lake St. Peter and at Lavaltrie, upstream in the river. Ice booms were successful but pile clusters did not perform well because the lake bed was probably too weak for the pilings to sustain the high ice forces. Artificial islands of three types were built to anchor the ice cover. The most stable type for the existing conditions is shown in Figure 3-19a. The second type (Figure 3-19b), which cost much less to build, is only as high as the mean winter high water level. A third type was formed by placing riprap around the substructures of old light piers. The islands were successful in forming and retaining a stable ice cover, and the winter navigation season was increased by an average of 30 days. In more recent years, additional islands and booms have been installed, and navigation to Montreal now lasts the entire winter. The islands, especially the low ones, require maintenance because the foundations have settled and the slopes have been eroded by moving ice.

(3) In 1980 three artificial islands were constructed in Lake St. Louis on the St. Lawrence River, upstream of Montreal. The islands are permanent and located east of Ile Perrot and north of the navigation channel (Figure 3-20). The islands were designed and constructed to help stabilize the ice cover north of the navigation channel, particularly during the spring breakup and the opening of the navigation season, eliminating the problem of large ice floes obstructing navigation. The effectiveness of the artificial islands has not been fully assessed.

(4) Artificial islands have been helpful in some locations, but they were chosen only after the ice movements had been studied. These islands provide good lateral stability to the ice cover, but a small change in water elevation will fracture the ice near the islands. Ice on the lee side may move away from the island, but ice on the windward side will remain in position. Islands armored with stone cost more initially but have lower maintenance costs.

e. Timber cribs. Timber cribs are enclosed frameworks built of timber and packed with stone to make strong, stable structures. Many small dams were built using this type of construction and have lasted for 80 years or more. Log boom docks are usually stone-filled timber cribs.

(1) An example of ice-restraining timber cribs is at the Narragaugus River flood control project, 1.6 kilometers (1 mile) upstream of the seacoast town of Cherryfield, Maine (Figure 3-21). The upstream face of each crib is sloped. Treated timbers were used in the construction. Three cribs are located in a triangular pattern about 38 meters (125 feet) upstream of a 2.1-meter-high (7-foot-high) dam and spillway. The ice cover normally contacts the crib at approximately midheight. The effectiveness of the timber cribs has not been measured, but they have remained in good condition for over 20 years. During this period severe ice jams have not occurred in the town, but the contribution of the timber cribs is unknown. The dam is undoubtedly the most important part of the project; the importance of the delay in ice cover movement at the dam caused by the cribs depends greatly on the tide water level.

(2) Timber cribs have been used to support navigation light towers in several locations, such as Lake St. Francis and Lake St. Peter near Montreal on the St. Lawrence River. In this capacity, they have also helped to keep the ice cover in place, but their usefulness on large lakes is in doubt. On poor foundation material, the crib is supported by timber pilings (Figure 3-22). Four small light piers were built on this type of subsurface structure in 1958 in Lake St. Francis. After receiving structural damage from ice thrust, more piles were added and the concrete cap was changed from a flat slab to a smaller cylinder. The resistance to ice thrust based on a stability analysis was thus increased to between 2.9 and 4.6×10^4 kg/m (between 10 and 15.5 tons/ft). Later, however, the cribs were replaced by conical, concrete light piers designed for a much larger ice force of 1.52×10^5 kg/m (51 tons/ft).

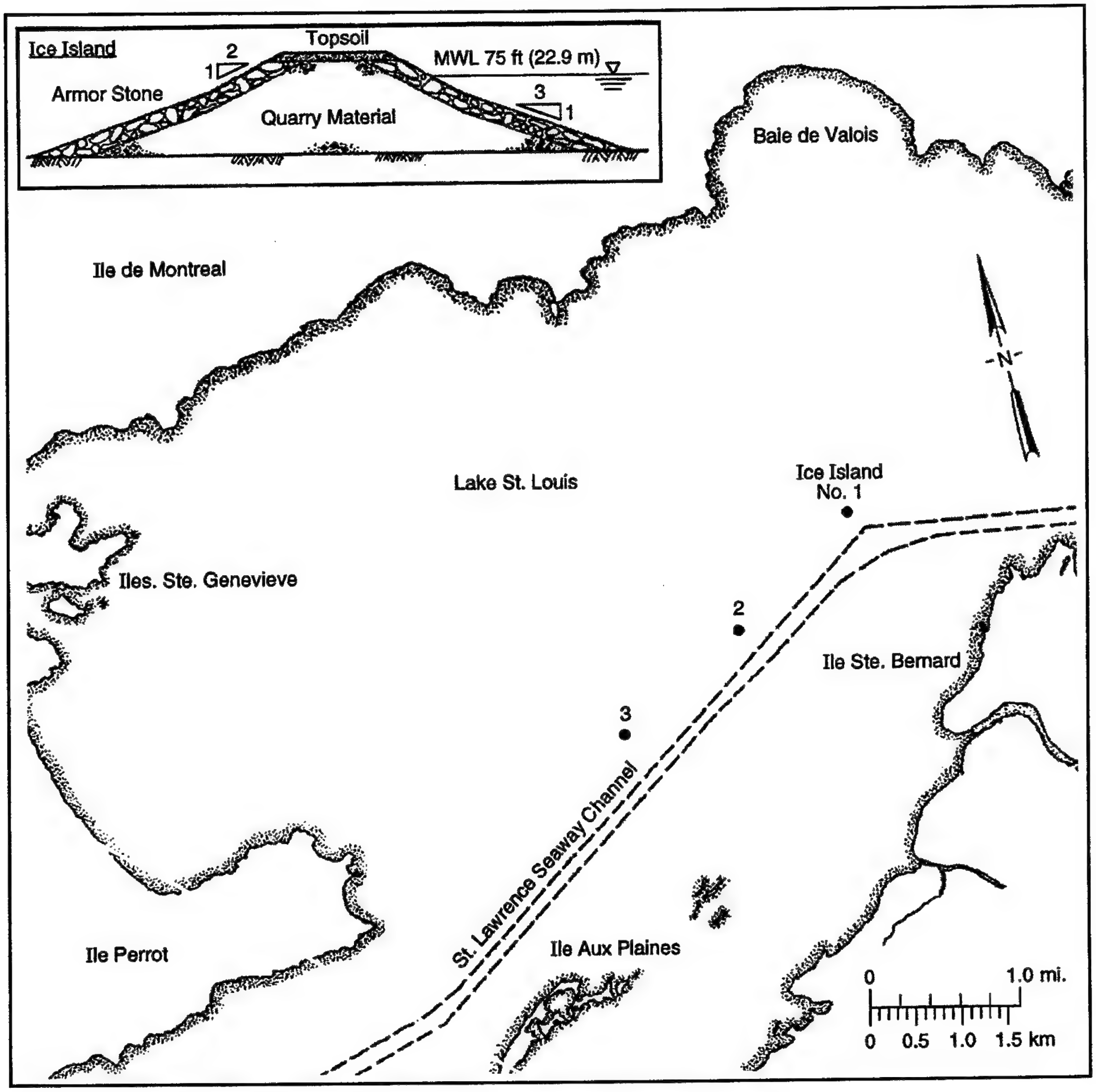


Figure 3-20. Artificial islands in Lake St. Louis, St. Lawrence River

f. Weirs. Weirs are low-head dams built across streams to raise the water level. A weir of sufficient height forms a diversion pool with the low velocities that permit the formation of an ice cover. This, in turn, precludes the formation of frazil ice and anchor ice. The ice cover is restrained by the streambanks and the structure because of the narrow width. The weir can be built from stone, concrete, or timbers (Figure 3-23). A common feature is the capability of adding flashboards or stop logs to increase water levels for winter operations.

(1) The performance of a low-head weir as an ice-control structure was observed by U.S. Army Corps of Engineers personnel on the Israel River in New Hampshire (Figure 3-24). The site was once the location of a small hydropower dam. The weir was constructed using rock-filled gabion baskets containing an impervious sheet piling and covered by a concrete cap. The low-flow discharge passes

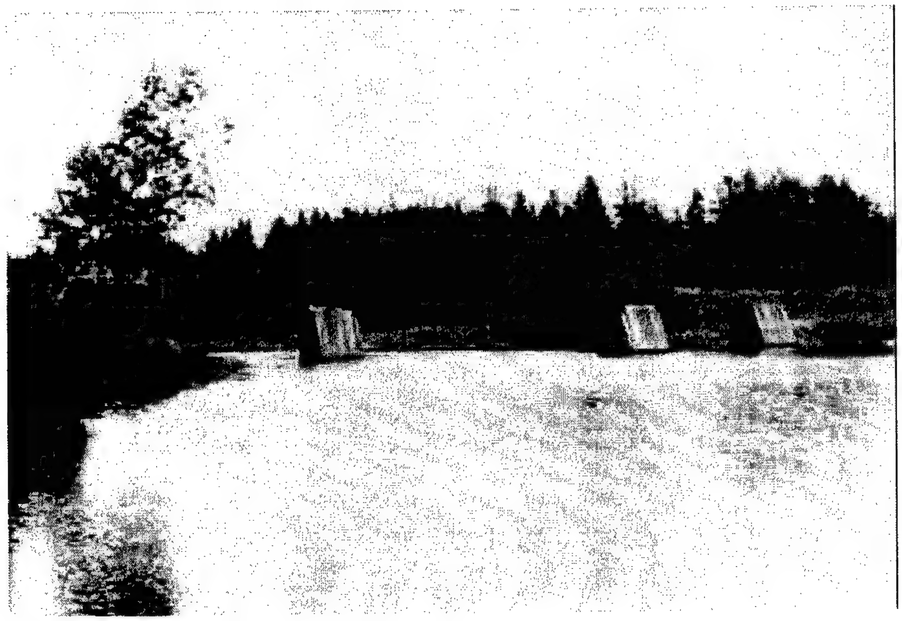


Figure 3-21. Ice-holding timber cribs in the Narragaugus River, Maine

through four 1.2-meter-wide (4-foot-wide) spillways. Indications were that the weir has only a small influence on the ice regime of the river.

(2) Weirs can help other structures to promote the formation of an ice cover by reducing the local flow velocities in the pool. An ice-control arrangement in the St. Lawrence River at Massena, New York, used a stone weir to raise the water level at an ice-control boom. The stones had to be about 1.5 meters (5 feet) in diameter to be stable. The boom consisted of a series of floating scows positioned between timber cribs. The flow velocities were 3.0 to 4.6 m/s (10 to 15 ft/s). Construction of the St. Lawrence Seaway project in the late 1950s eliminated this site.

(3) A 12-meter-high (40-foot-high) ice-control dam (Figure 3-25) was built on the Chaudiere River at St. George, Quebec. Upstream of the spillway section, ice gratings fixed between concrete piers retain ice floes. The gratings, however, are located far enough upstream of the weir crest to have little effect on the weir's performance. Operable gates to one side of the spillway section are used to maintain a fairly constant pool elevation.

g. Pilings and dolphins. Piles that support a wharf or pier can anchor or retain an ice sheet. The effects of the vertical uplifting forces and horizontal forces from ice sheets must be considered for structures using exposed pilings. Piling clusters, or dolphins, have received greater consideration for restraining ice. These are usually formed by a cluster of closely driven piles secured at the top with wire rope. Model tests of a line of individual pile clusters indicate that good ice retention is possible. An installation of several timber clusters in Lake St. Peter in 1962, however, failed early in winter. The cause was attributed mainly to a very weak foundation and large ice forces. Tests show that dolphins have surprisingly little resistance to steady lateral pulls.

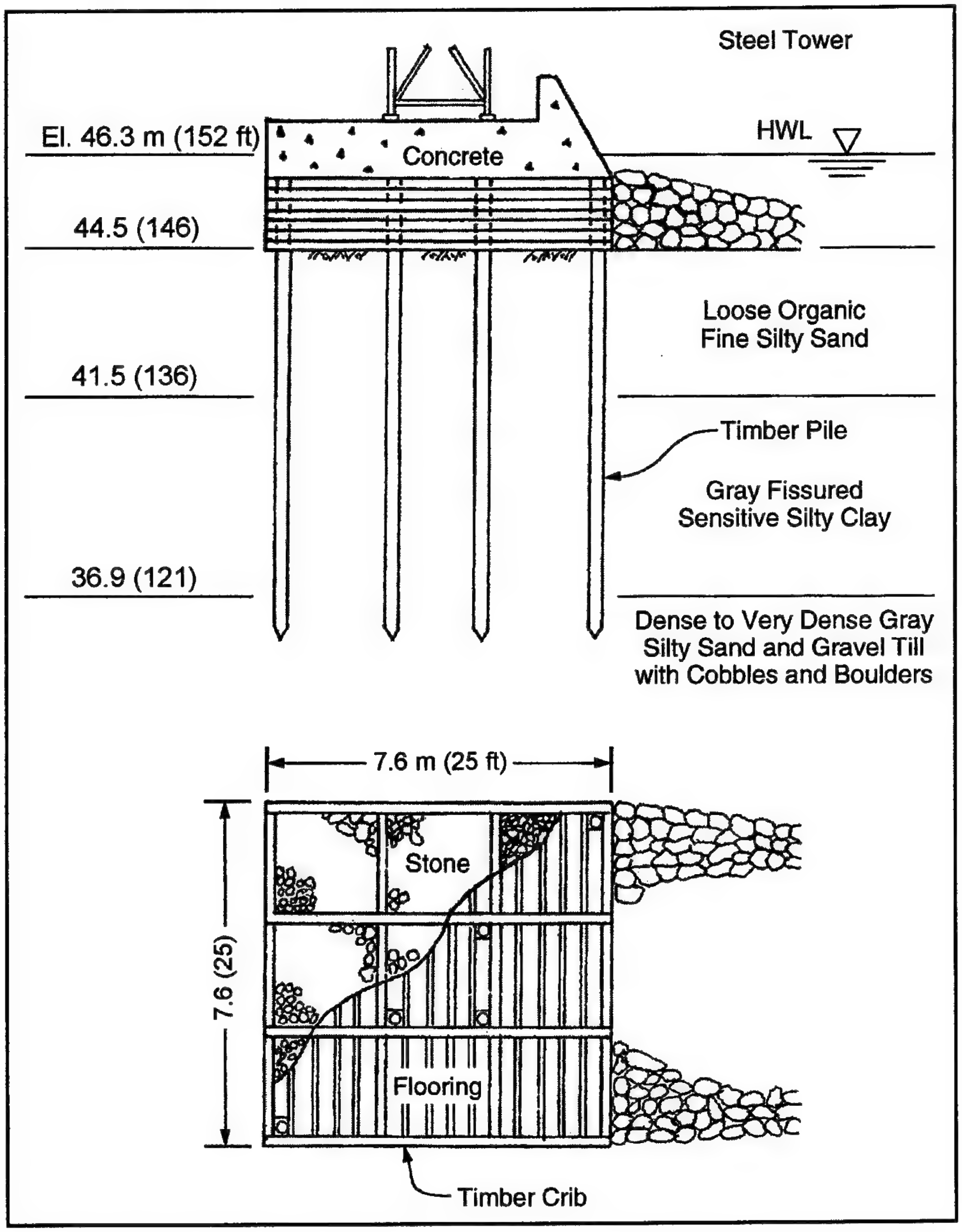


Figure 3-22. Stone-filled timber cribs and concrete caps used as light tower bases

(1) A dolphin in the Cap Cod Canal, Massachusetts, resisted ice forces for several years but eventually failed from the action of ice floes moving in water currents with velocities up to 3 m/s (10 ft/s). The replacement dolphin in the 10-meter-deep (33-foot-deep) water was made of 21 steel H-piles.

(2) Besides vertical and horizontal forces, the effect of ice abrasion is an important consideration. It is possible for ice to sever timber pilings in a matter of hours. Oak pilings are fairly ice resistant, but timber structures may last only about 20 years, partly as a result of ice abrasion. Timbers can be protected

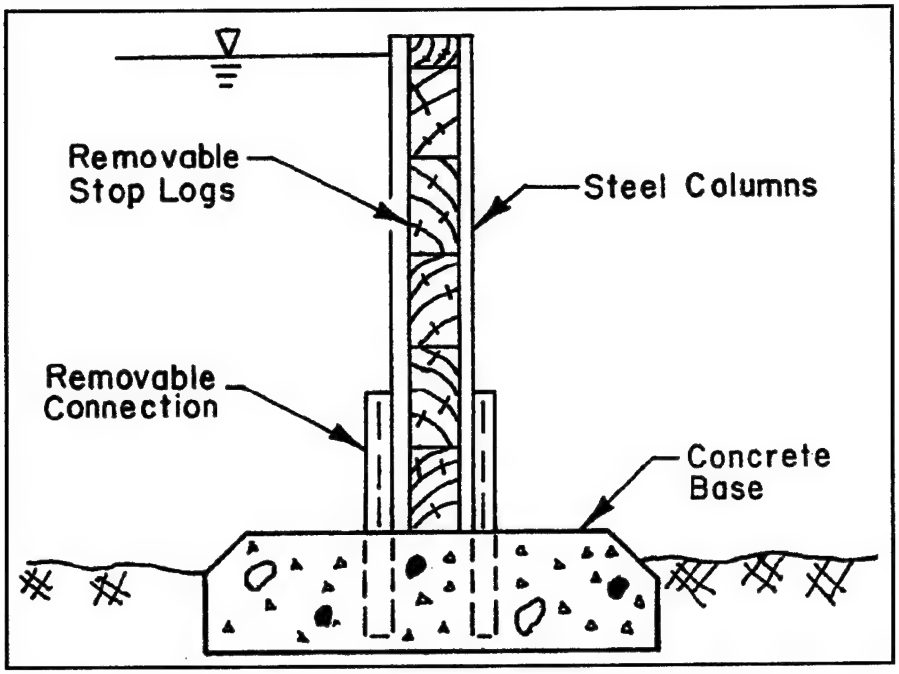


Figure 3-23. Timber weir

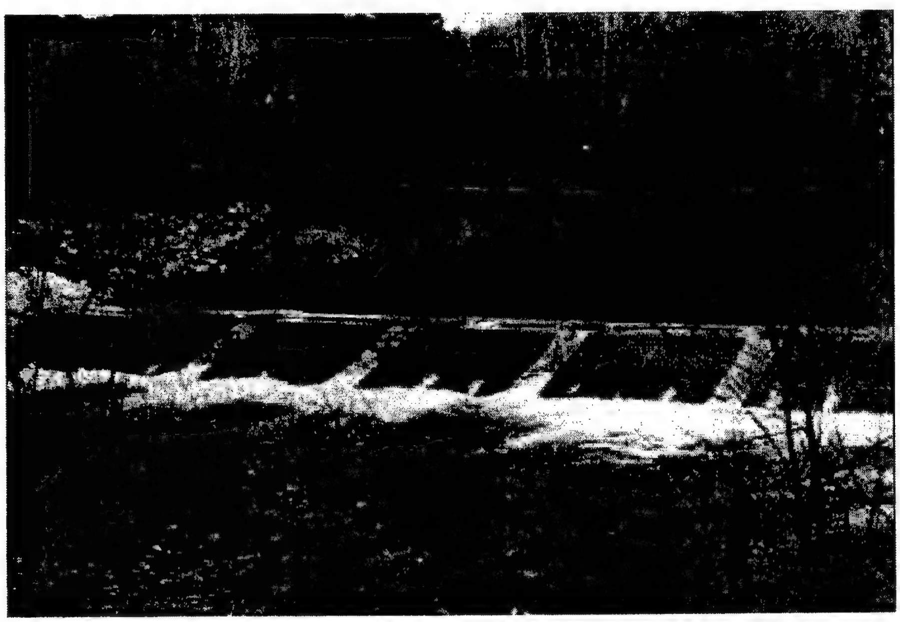


Figure 3-24. Ice-control weir, 2.0 meters (6.5 feet) high, on the Israel River, New Hampshire, with a moderate flow passing over the top

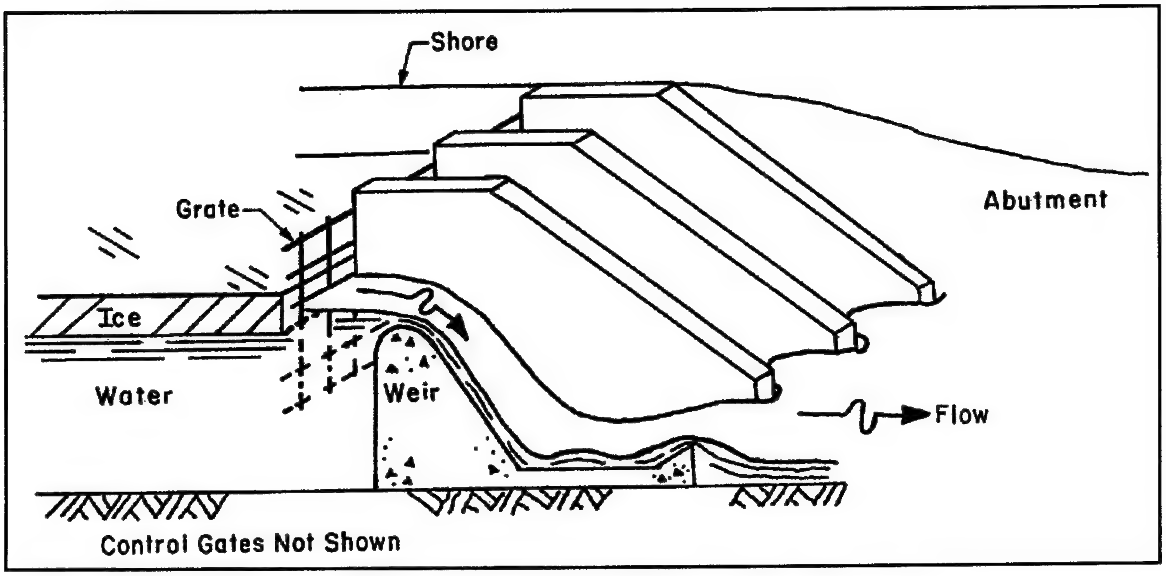


Figure 3-25. Weir and stationary grating on the Chaudiere River, Quebec, Canada

by steel armor. Concrete can also be adversely affected by ice abrasion and by the spalling of material from repetitive freezing and thawing of ice on its surface.

h. Ice piers. Ice piers are structures set in the river to protect a fleeting area against moving ice. The piers take the brunt of the impact and pressure forces and either stop the ice or deflect it to move around the ice pier location. Barges and tows are anchored downstream of the ice piers, which have anchoring chains for this purpose. The piers may be rectangular reinforced concrete structures, 4.9 × 7.6 × 3.0 meters (16 × 25 × 10 feet) high above water, or they may be similar to cylindrical sheet piling cells as in Figure 3-26.

i. Drift deflectors. A drift deflector is usually a barge or barges set on a diagonal with one end against the shore to deflect material floating with the currents outwardly away from shore. This method is seen to work well on the inside of bends, where the normal water currents have a natural component away from the shore. A fleeting area immediately downstream could be protected by a drift deflector. A large ice deflector arrangement was proposed for installation (but not built) at Montgomery Locks and Dam, on the Ohio River, to reduce the amount of ice entering the lock during winter navigation. As shown in Figure 3-27, three barges and a mechanical linkage type of anchoring were proposed. A towboat was to move it between its open and closed positions and also break ice. A similar function is sometimes provided by barge tows on the Mississippi River waiting for lockage at Chain of Rocks Canal and at Lock and Dam No. 17. Ice passage at these sites is no problem.

3-4. Ice Control by Structures Built for Other Purposes

The formation and retention of ice covers can be aided by structures that were not built for that purpose. Flows at any dam with discharge regulation capability can be manipulated to help an ice cover form. Other structures, such as wicket dams and bridge piers, aid in the formation and retention of ice covers simply by their presence.

Figure 3-26. Cylindrical sheet piling mooring cells upstream of a navigation dam can help to stabilize the ice cover in winter

a. Hydroelectric dams. It is possible to aid the formation of an ice cover on rivers by increasing flow depths and decreasing flow velocities at strategic times during the early winter. This capability must be accompanied by a comprehensive understanding of the hydraulics and ice conditions on the river and how it responds to various meteorological influences. Usually, ice sheet retention structures are needed too.

(1) An example is the operation of the Beauharnois Canal and powerhouse on the St. Lawrence River about 40 kilometers (25 miles) west of Montreal, Quebec. Here, the Coteau diversion structure sends nearly all the flow of the St. Lawrence River at Lake St. Francis down the 24- kilometer-long by 914-meter-wide (15-mile-long by 3000-foot-wide) canal to pass through the powerhouse and into Lake St. Louis. The installed capacity of the plant is 1564 MW.

(2) The Beauharnois Canal has a forebay ice boom spanning the canal and six upstream booms that contain gaps allowing ice floes to pass through and collect at the forebay boom. The forebay boom is instrumented for forces so that the operators can tell when an ice cover is starting there, even when the canal is obscured by blizzards. In early winter, a small icebreaker breaks ice in Lake St. Francis to increase the collection of ice on the canal. At this time, average flow velocities in the canal are reduced from 0.70 to 0.46 m/s (from 2.3 to 1.5 ft/s), which allows an ice cover that is smooth on its underside to form there. Higher velocities would cause a rougher ice cover to develop, reducing power generation. The formation process takes from a week to 10 days; after the ice cover stabilizes behind the booms, the flows are increased gradually to near-summer levels, 0.70 m/s (2.3 ft/s). The short-term flow reductions are more than compensated for by improved flow conditions throughout the remainder of the winter. The force instruments monitor the stability of the ice cover throughout the winter. Over the many years it took to develop this equipment and these procedures, the power plant has improved its winter output by approximately 200 MW.

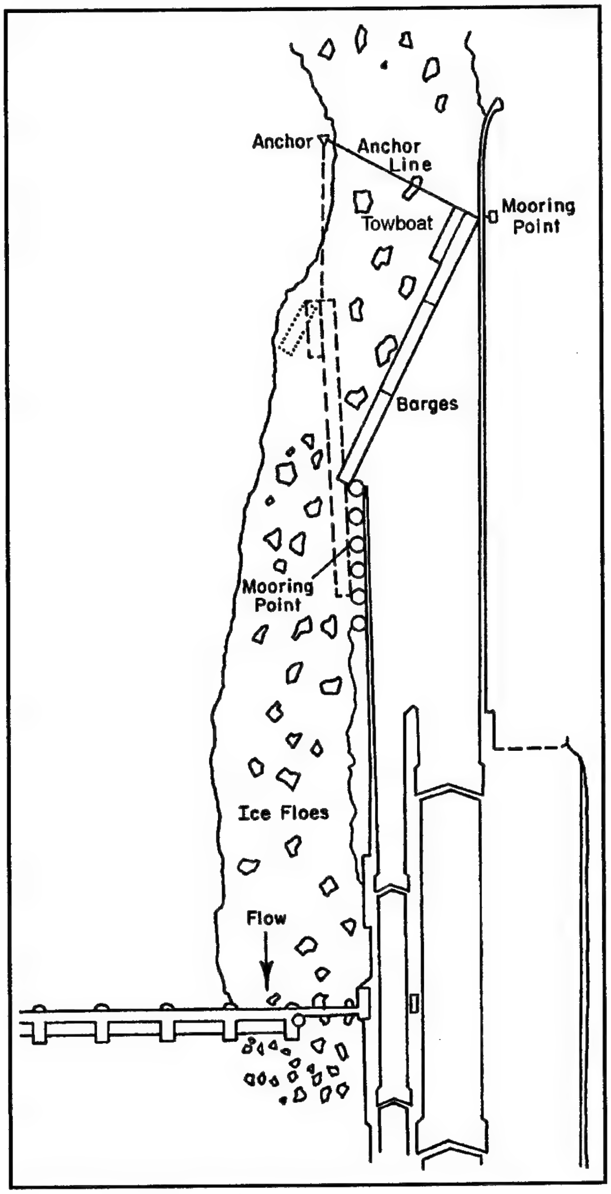


Figure 3-27. Diagram of a proposed movable ice deflector composed of three barges and a towboat, which could be deployed to protect an upper lock entrance from ice accumulation

(3) Another example of operator control is the International Section of the St. Lawrence River, which is controlled by the hydroelectric plants at Massena, New York, and Cornwall, Ontario. Six ice booms are located about 64 kilometers (40 miles) upstream of the dam. The progression of the ice cover is monitored closely. River flows are adjusted according to the location of the ice edge and the weather conditions so that a smooth ice cover will develop; this minimizes head losses attributable to ice during winter.

(4) As the ice edge nears the high-velocity reach a couple of miles below Iroquois Control Structure, the vertical lift gates are lowered 4.6 to 6.1 meters (15 to 20 feet) into the water. This cuts off the supply of ice floes to the downstream reach, where a hanging dam might develop. The unconsolidated ice cover continues to develop from the dam up to its local limit of the Galop Cut at Cardinal, Ontario.

b. Wicket dams. A wicket dam comprises a series of rectangular elements or wickets that are propped side by side and on end to form a sloping dam face (Figure 3-28). A typical wicket measures 0.3 × 1.1 × 4.9 meters (1 × 3.5 × 16 feet). The elements are raised and lowered by a barge-mounted crane, and usually they increase the upstream water level from 1.8 to 2.4 meters (6 to 8 feet). They have been used on the Ohio and Illinois Rivers for maintaining minimum depths for navigation during times of low flows. As an added benefit, these structures help to form and maintain ice covers.

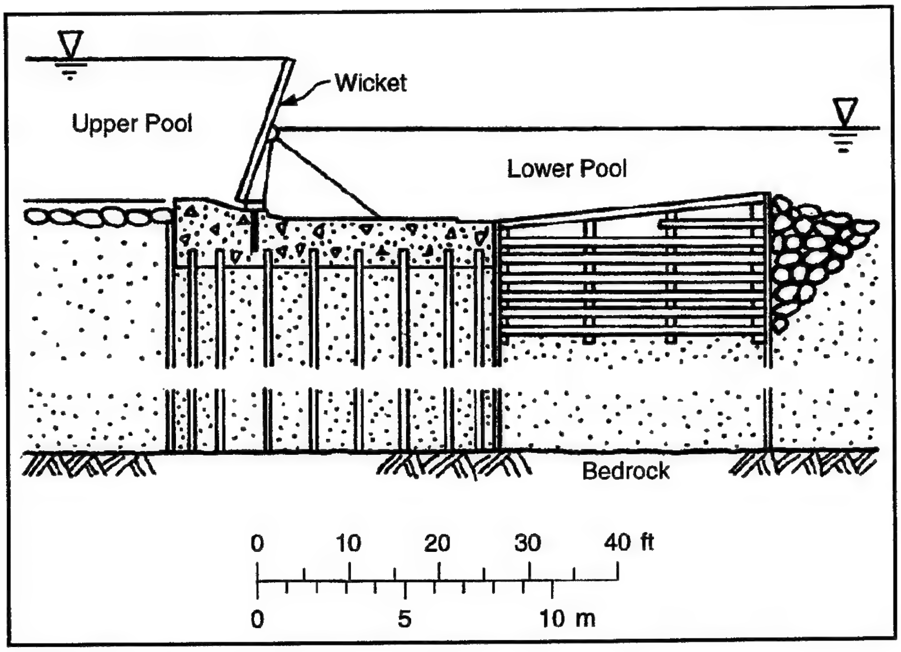


Figure 3-28. Typical section of a navigable pass portion of a wicket dam

c. Light piers and towers. Light piers and towers are used to mark the locations of navigation channels and courses. These structures can be built on land, but many are built offshore, where they become frozen into the ice sheet. Should the ice sheet break free from shore, a high force can be applied to the pier or tower. If the force is great enough, either the ice or the tower will yield. Ice loading also develops on a light pier structure when the ice on the channel side of the structure has been broken or removed while the ice cover is still intact between the light pier and the shore. The thrust is probably from thermal expansion of the solid ice.

(1) Timber cribs were used for substructures until about 20 years ago, but reinforced concrete and steel shells are now used. New light piers are usually cone-shaped where they touch the ice; the slope of the cone is usually 45 degrees. A typical light pier is shown in Figure 3-29. As in most designs where ice is involved, it is important to select a realistic design ice thickness. For this light pier, a thickness of 0.6 meters (2 feet) was selected based on previous measurements of 0.46 to 0.49 meters (1.5 to 1.6 feet). More recent measurements showed, however, that ice thicknesses may reach 0.79 meters (2.6 feet); a design ice thickness of 0.9 meters (3 feet) is now used.

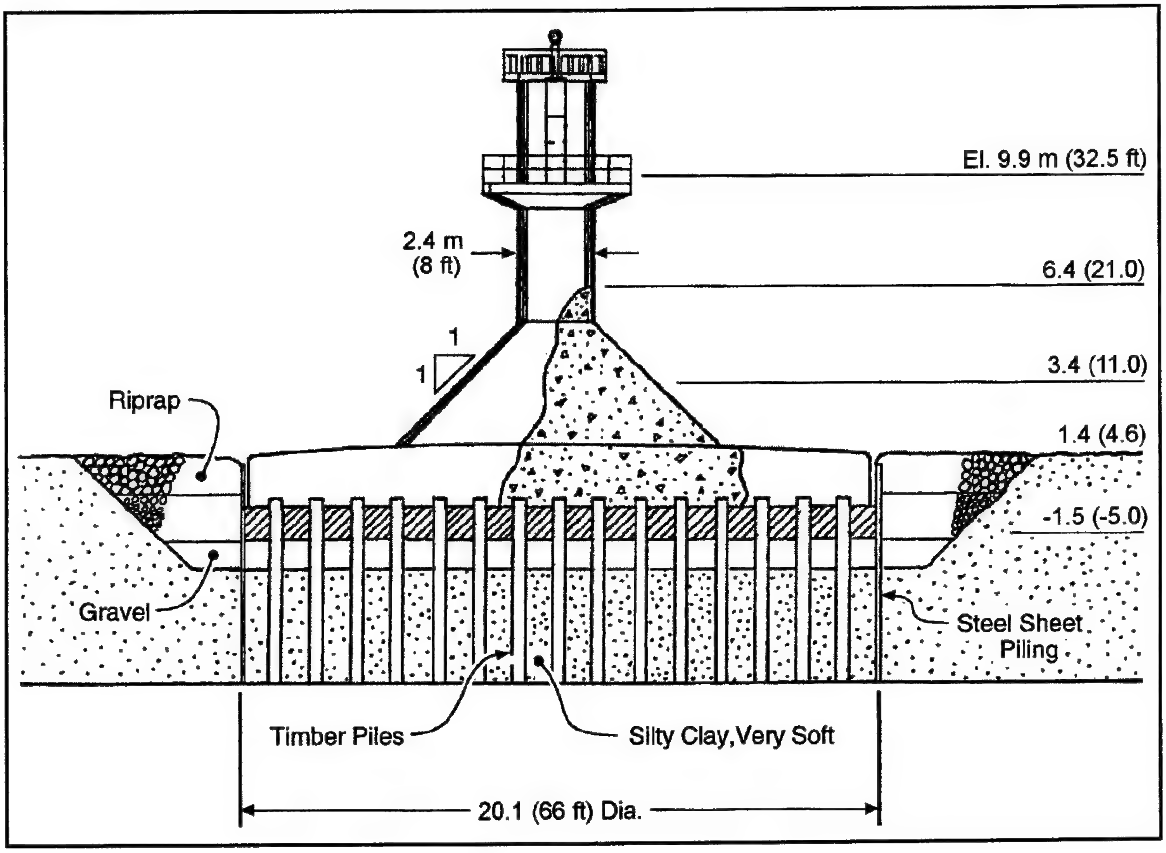


Figure 3-29. Light pier built in 1968 on Lake St. Peter, Canada

(2) A U.S. Coast Guard light pier that was built in Lake St. Clair is shown in Figure 3-30. The base of the light pier is stabilized by a ring of sheet steel pilings and a central arrangement of driven piles. Its conical top is welded to the upper end of the sheet piling ring. The core of the pier is filled with stone, while reinforced concrete fills the cone and the top of the pile cylinder. A relatively small tower and light are mounted on top.

(3) The all-steel light tower shown in Figure 3-31 is located about 4.8 kilometers (3 miles) offshore in Maumee Bay on Lake Erie. A key to the tower's survival is undoubtedly its large wheel-like base, which is fixed in place by several pilings.

d. Bridge piers. Bridge piers often constrict the river flow, and ice floes may collect at the piers in early winter to form an unconsolidated ice cover. Border ice growth on the piers can increase this narrowing effect at the water's surface if the spacing is small. Under some circumstances, however, this channel narrowing may lead to water velocities that are too high to allow an ice cover to form. Dynamic, static, and thermal ice pressures and ice abrasion must be considered in designing bridge piers.

e. Breakwaters. A breakwater is a structure protecting a shore area, harbor, anchorage, or basin from wave action. Stationary breakwaters can increase ice cover stability and bear the brunt of forces from moving ice that would otherwise affect the areas protected by the breakwaters. This is not generally the case with floating breakwaters.

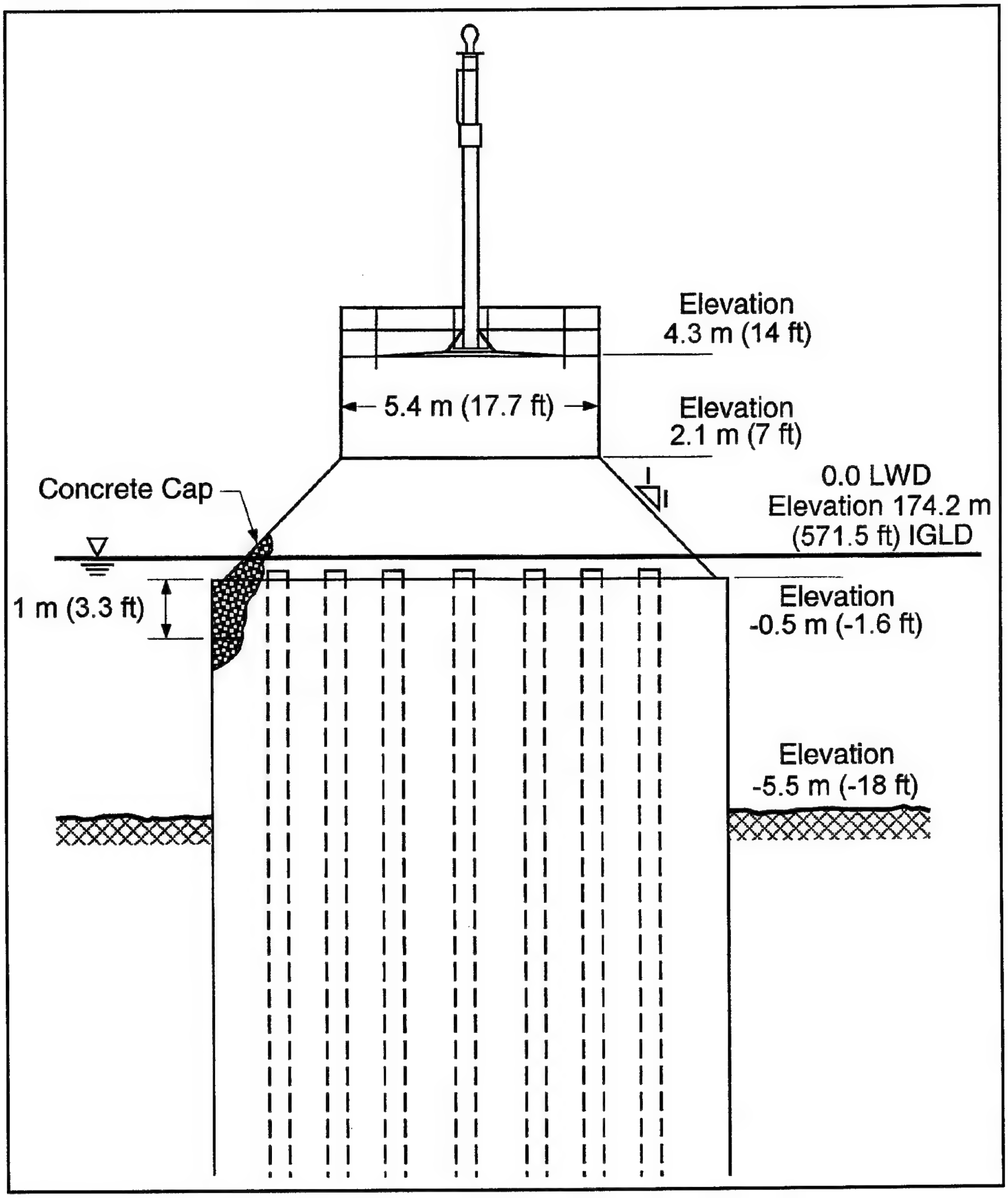


Figure 3-30. Light pier in Lake St. Clair, Michigan

(1) Breakwaters may be constructed from rubble mounds, cast concrete elements, concrete caissons, sheet-piling cells, or cribs, or be prefabricated and moved into place. In the United States, breakwaters built on the open coast are generally of rubble-mound construction. Occasionally, they are modified into a composite structure by using a concrete cap for stability. An innovative 5.8-meter-high (19-foot-high)

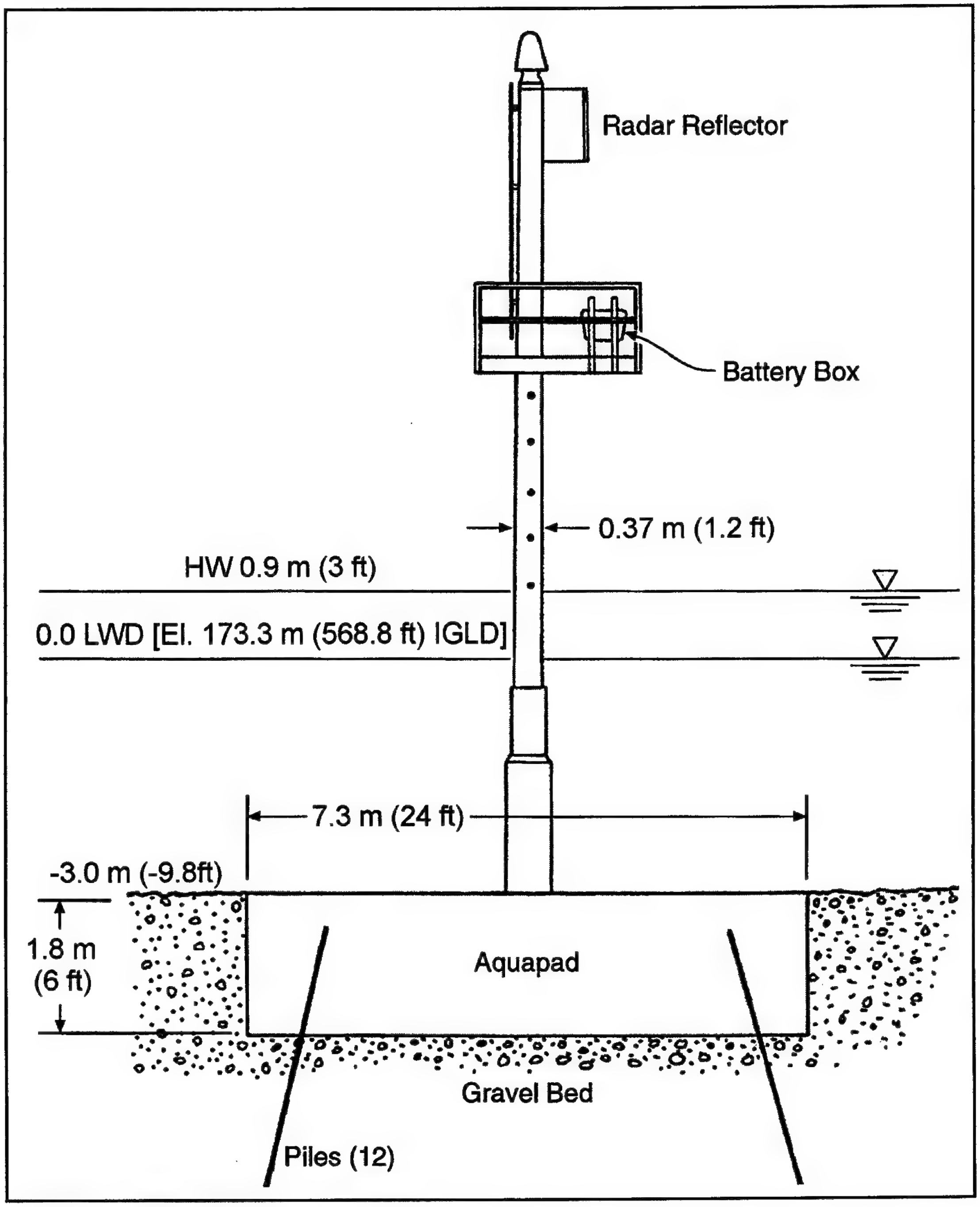


Figure 3-31. Steel light tower on Maumee Bay, Lake Erie. The tower has a square cross section

pack ice barrier constructed of ballasted steel pipe protects the coast line of the Saroma Lagoon in northern Japan.

(2) Normally, the wave forces on shore structures are comparable in magnitude to the maximum probable pressure that might be developed by an ice sheet. As the maximum wave forces and ice thrust cannot occur at the same time, usually no special allowance is made for overturning stability to resist ice thrust. However, where heavy ice may occur, either in the form of a solid ice sheet or floating ice fields, adequate precautions must be taken to ensure that the structure is secure against sliding on its base. Other problems such as gouging, abrasion, local failures, ice ride-up, and ice cover transport of materials exist.

3-5. Ice Control Not Using Structures

a. Channel improvements. The cost of channel improvements is usually very high, and often there are many other social and environmental factors that influence their implementation. The best way to predict how certain improvements will affect the winter operation of a waterway is to accurately simulate the present and future conditions in a physical, hydraulic model. Changes that reduce average water velocities and velocities at local points of acceleration generally help to form and maintain an ice cover. The most reliable improvements are to make the channel deeper and straighter and to remove midstream obstructions that cause high-velocity zones. However, it is important to consider the effect of channel modification on the breakup ice regime. For example, deepening the channel at a location to reduce velocity and encourage ice formation may create an initiation point for a breakup ice jam.

b. Ice-sheet tying. Large, broken pieces of ice can be tied together with rope to keep them from moving from one location and to another. Broken ice can be tied to shorefast ice in the manner that was used on the Mississippi River at Prairie du Chien, Wisconsin, in 1981 for an emergency ferry track. Holes were drilled through the ice about 0.9 meters (3 feet) from both sides of the crack. A forearm-sized stick of wood with a rope centrally attached was set across each hole beneath the ice. The two rope ends were tied together across the crack to make a tight connection. The ropes were tightened by twisting them with another stick (Figure 3-32). Braided rope 0.6 to 1.3 centimeters (1/4 to ½ inch) in diameter worked best. Ties spaced from 3 to 9 meters (10 to 30 feet) apart were sufficient. A line spanning several sheets provided more reliability in some instances. Unless they were covered with snow, lines frozen to the surface melted free because of solar radiation.

c. Ice-sheet bridges. A section of border ice can be sawed out and placed diagonally across the river. Drift ice coming from the upper reaches of the river is halted by this barrier and freezes into a solid ice cover. The purpose of bridges is to develop ice covers on rapids, where tremendous quantities of anchor ice and frazil ice are generated. In practice, the ice bridge would be created below the rapids with the idea that an ice cover would progress upstream through the rapids. This technique has been used successfully to promote ice arching at a channel constriction on the Lule River in Sweden, upstream of the Vittjarv power station. Also, U.S. Coast Guard icebreakers have dislodged large floes from Soo Harbor, Michigan, allowing them to drift to the head of Little Rapids Cut to form an ice arch.

Section II
Thermal Ice Control

3-6. Design of Air Bubbler Systems to Suppress Ice

Air bubbler systems can suppress ice formation and allow navigation in harbors, ports, and waterways during periods when thick ice would otherwise halt it. This section provides general guidelines useful in

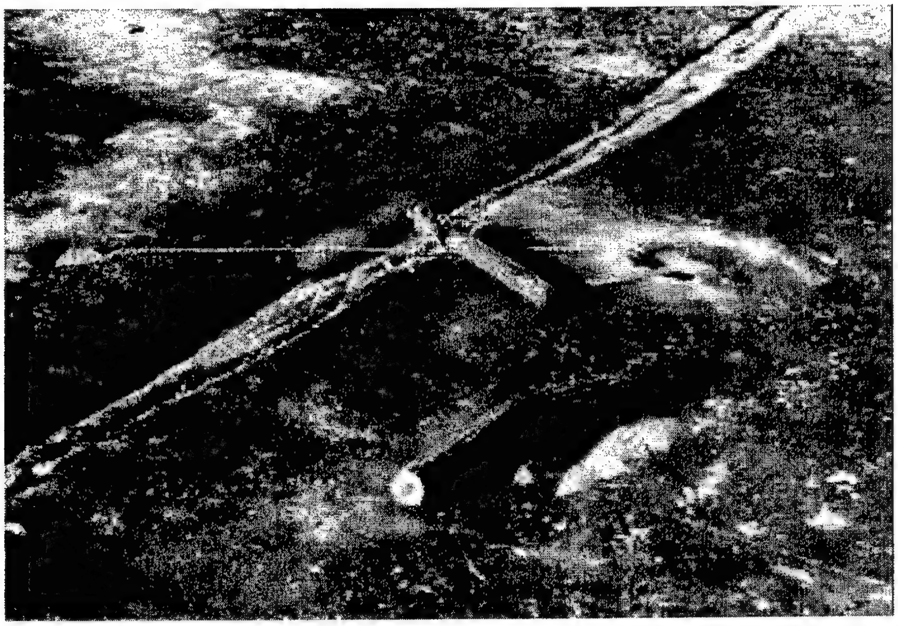


Figure 3-32. Ice sheet retention by tying with lines, Mississippi River, Prairie du Chien, Wisconsin, 1981

design and feasibility studies of such systems, briefly describes a computer program now available at CRREL for use in detailed deicing decisions, and illustrates the nature of the suppression actually effected by a bubbler system with an example simulation.

a. Principles of operation. A bubbler system uses an air-driven water jet to induce convection of warm water against an ice cover, thereby melting it or suppressing its growth. Figure 3-33 presents a cross-sectional schematic view of a bubbler system. A compressor (A) delivers air into a supply line; (B) the air flows through the diffuser line (C) and is discharged through orifices distributed along its length. A plume of bubbles forms and continually entrains the surrounding water as it rises (region D). Near the surface (region E), the plume spreads under the ice cover, initially in a relatively thin layer (region F), but gradually entraining more water and dissipating (region G). Convection transfers the thermal energy contained in the water to the underside of the ice cover in regions E, F, and G, causing it to melt.

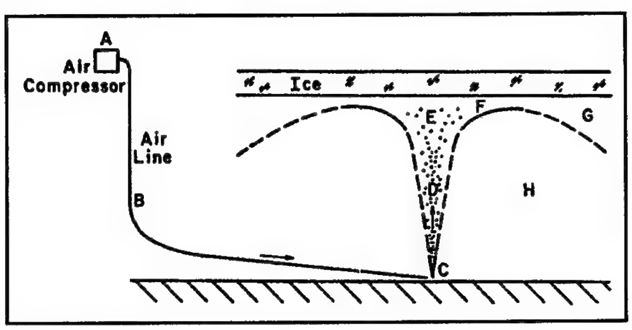


Figure 3-33. Schematic diagram of bubbler system

(1) The most important requirement for successful performance of an air bubbler system is a supply of warm (at least 0.2°C (32.4°F)) water. In enclosed harbors, large lakes, or connecting channels between large water bodies, winter water temperatures are generally adequate to supply the necessary thermal energy to support local suppression of an ice cover. In faster flowing rivers (mean velocity greater than about 0.4 to 0.6 m/s (1.3 to 2 ft/s)), bubbler systems cannot be expected to be very effective, for two reasons. First, in such rivers the winter water temperatures during the period of ice cover seldom exceed 0.1°C (32.2°F); hence, the thermal energy necessary for melting is not present. Second, at such velocities, the warm water flowing against the undersurface of the ice cover is already transferring heat to the ice cover as fast as a bubbler system could; hence, melting is happening as fast as it would with a bubbler system. Before a bubbler system can be designed, or the operational strategy (such as intermittent operation) formulated, measurements should be made to determine the temperatures present and the extent of the thermal reserve.

(2) Other performance requirements that must be assessed are the width of open water or extent of thin ice required for the system to be effective. Even well-operating bubbler systems with adequate warm water available will freeze over during the short periods of intense winter cold. The open water produced will seldom be as wide as the usual channel. However, for navigation the role of ice suppression is to provide a relief zone in an otherwise solid ice cover. This relief zone can be either within or to one side of the channel. Vessels can often operate effectively with such a relief zone where they could not operate in a uniformly thick ice cover.

b. Design parameters. Parameters that the designer of a bubbler system can control are the compressor output pressure and air discharge rate; the supply line diameter (length of which is generally dictated by the site geography); diffuser line diameter and submergence depth; and orifice diameter and spacing. The designer should realize that the various parameters interact with each other to determine the ultimate performance of a particular system.

(1) Output pressure must be sufficient to overcome the hydrostatic pressure at the diffuser line depth and the frictional losses in the supply and diffuser lines, and yet provide a pressure differential at the orifices to drive the air out at the desired rate. The required air discharge rate is determined by the system geometry (length, pipe diameters, etc.). Typical air discharge rates used in field installations have been on the order of 2.8×10^{-3} m^3/minute per meter (0.03 ft^3/minute per foot) of line. A given system is generally either discharge-limited or pressure-limited by the compressor characteristics and system geometry. Ideally, a balanced design would result in discharge/pressure output at the peak efficiency point of the compressor's performance.

(2) The supply and diffuser line diameters should be large enough that the pressure drop attributable to friction along the line is small, so that a uniform air discharge rate can be maintained along the line. Methods exist for the iterative solution of the manifold-type problem and these methods have been incorporated in the computer simulation described below. Often, a small increase in line diameter will significantly reduce friction losses, resulting in considerably more uniform air discharge rates. Typical line diameters at field installations are between 3.8 and 7.6 centimeters (1.5 and 3 inches).

(3) Submergence depth is generally governed by operational limitations, such as depth of water body or required clearance for vessel drafts. The deeper the submergence is, the more water will be moved by a given discharge rate and hence the more suppression effected, but a larger compressor pressure is needed as the depth increases. In some cases, very large depths require pressures that make it desirable to suspend the line above the bottom.

(4) Typical orifice diameters are on the order of 0.12 centimeters (3/64 of an inch), and typical spacing is about one third of submergence depth. Orifice diameters that are too large can result in all the air leaving the diffuser line at one end. The pressure, diameter, and discharge are interrelated and cannot be easily separated from the total system design.

(5) If the far end of a diffuser line can be opened, water can be easily pumped out when the system begins operation after a shutdown. System performance is not affected by the type of pipe used (plastic or metal), so materials should be chosen on the basis of maintenance, reliability, and operational considerations.

c. Computer simulation. A computer simulation of the performance of an air bubbler system has been developed which allows typical winter air temperature records to be input, and it outputs the evolution of the thermal reserve, ice cover thicknesses, and width of open water. The program has been proven valid with field data obtained from an installation operated in 1974 at Howards Bay, Superior, Wisconsin. The program is written in FORTRAN, but could be easily adapted to other computer languages. The simulation is done in four parts, outlined below.

! Diffuser line analysis:

Input = diffuser and supply line lengths and diameters, orifice size and spacing, submergence depth, compressor output pressure.

Output = air discharge rates from orifices, air discharge from compressor.

! Induced plume analysis and heat transfer analysis:

Input = temperature profile at initial time.

Output = water discharge rates, impingement temperature, heat transfer rates to ice cover.

! Ice melting analysis:

Input = initial ice thickness profile, air temperature.

Output = evolution of ice cover thickness or width of open area, or both.

! Thermal reserve analysis:

Output = change in thermal reserve, new temperature profile.

d. Example simulation. Figures 3-34 through 3-37 show an example of the simulation results. Figure 3-34 shows the daily average air temperature variation, Figure 3-35 the initial water temperature profile, Figure 3-36 the variation in width of open water, and Figure 3-37 the variation in ice thickness at different distances from the bubbler centerline. The comparison of field observation to simulation results is shown in Figure 3-36. Note that the field installation was shut down after 45 days.

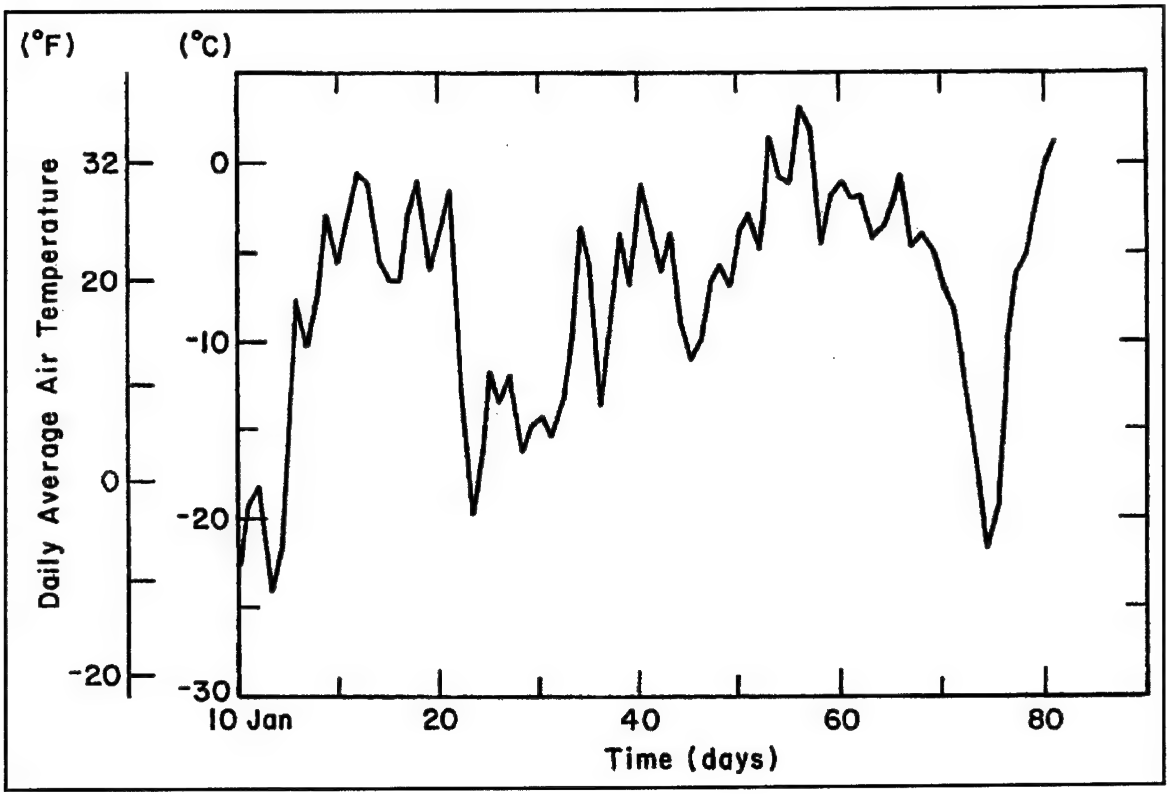


Figure 3-34. Average daily air temperatures at Superior, Wisconsin, 1974

3-7. Point-Source Bubbler System

"Line-source" bubblers are intended to suppress ice over long, narrow extents for uses such as navigation. Often, however, ice suppression is needed at one or more single locations, such as a pile, a local structure, or other places where a long "line" is inappropriate. A point-source bubbler can be used at such locations.

a. Flow characteristics. The difference between line-source and point-source bubbler systems is the geometry of the resulting flow field. The flow induced by a number of line sources tends to be two-dimensional, with the upwelling flow directed horizontally away from the line. The flow induced by a point source is conical to the surface with an outward radial flow occurring at the surface. In both cases the rate of melting, and hence the effectiveness, depends directly on the product of the water temperature and the local velocity. The velocity decreases with distance away from the location where the bubbles encounter the water surface, so that the largest melting rates occur directly above the air supply locations.

b. Temperature requirements. The conditions described for success of a line-source system are also necessary for the success of a point-source system. It must be emphasized that above-freezing water temperatures are required in the water body. Further, if many point sources are used, the thermal reserve in a small enclosed water body may become exhausted over the course of a winter; hence, prudent placement of a small number of bubblers is often more effective in such cases.

c. Design. The design parameters are much the same as for line-source systems. Information and assistance in the use of computer simulations written in FORTRAN to assess the performance of both

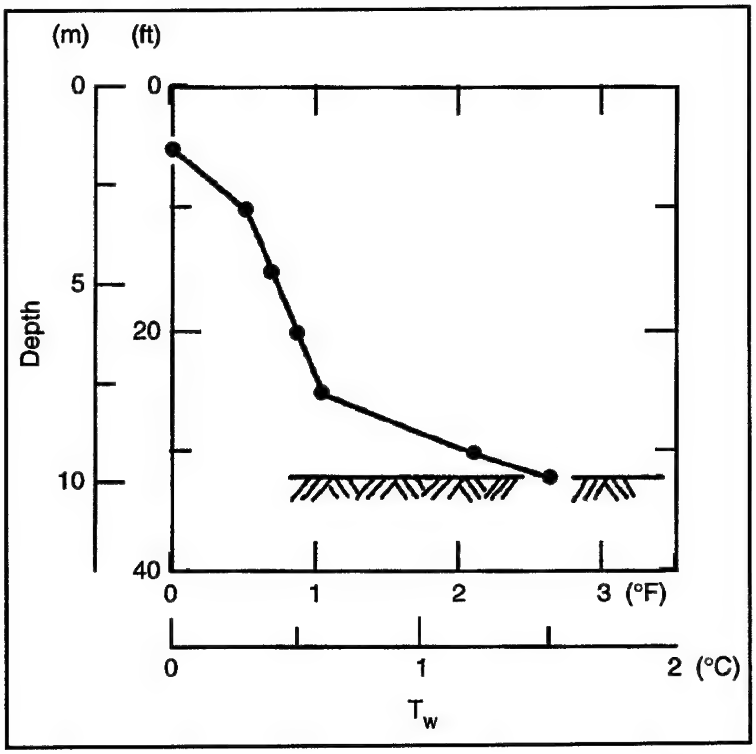


Figure 3-35. Water temperature, Howards Bay, Wisconsin, 1974

point-source bubblers and line-source bubblers may be obtained from CRREL. One further note is in order: it is known that the outward spreading radial surface flow will plunge below the surface at a radial distance of about six or seven times the depth. A point source bubbler will not be effective at greater distances from the air source location.

3-8. Use of Thermal Effluents and Warm Water for Ice Control

Most rivers have sources of warm water that either already suppress some ice formation or may be used to cause some ice suppression. The most obvious are power plants that discharge heated water into the river. Typically, there will be a narrow band of open water for some distance downstream of these plants when the river is otherwise ice covered. In other cases reservoirs, even with ice covers, may contain water above the freezing point of 0°C (32°F). When this water is released, it will flow some distance downstream before it begins to freeze. This section describes the effect on ice covers of these sources of warm water and provides approximate means of estimating this effect.

a. Sources of warm water. Besides the two main sources of warm water in winter mentioned above, there are other sources such as the discharge of treated sewage, warm waste water from industrial plants, and, occasionally, warm springs; but generally, all of these release too little heat to cause more than very local effects on the natural ice cover. In seeking to use warm water as an aid to river ice management, it is important to realize under what conditions the warm water may be effective, and the extent of the influence.

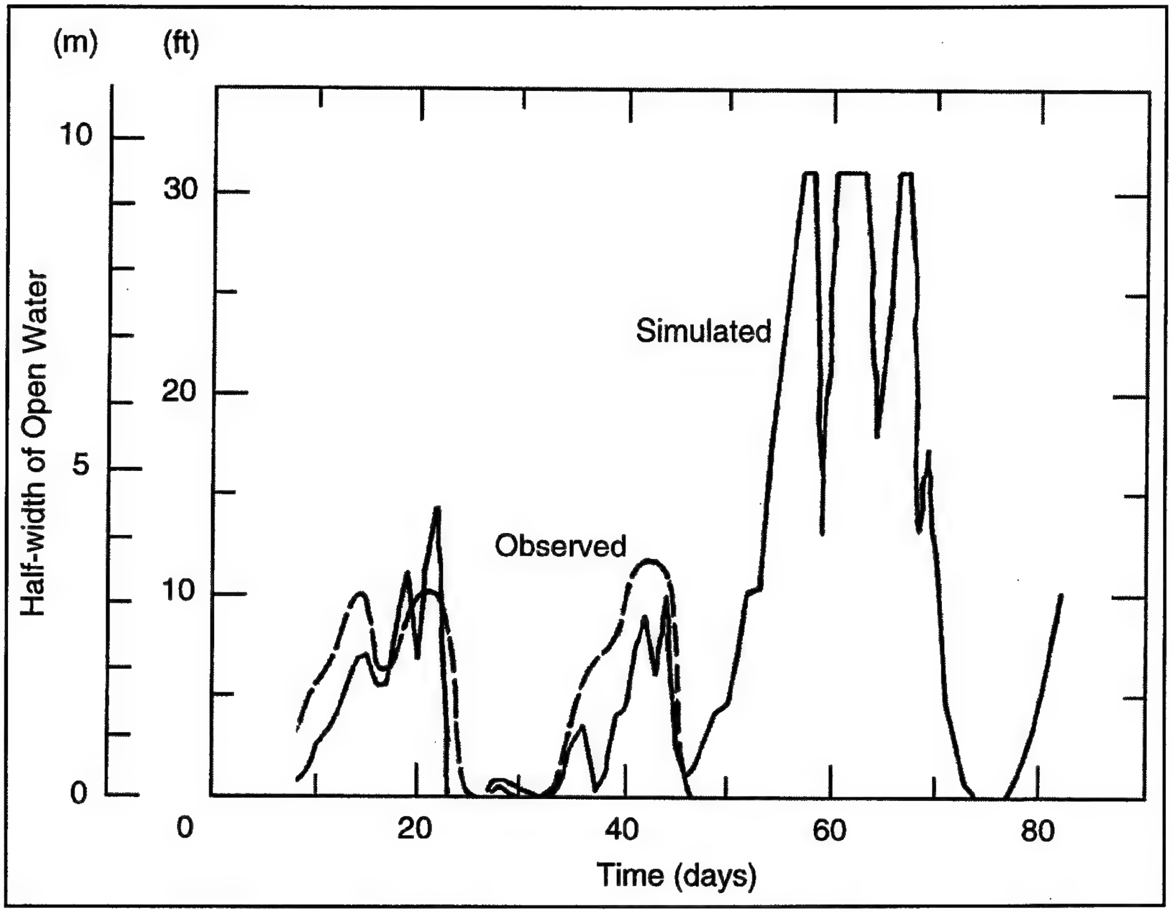


Figure 3-36. Half-width of open water, assuming no thermal depletion, Howards Bay, Wisconsin, 1974

(1) Both fossil fuel power plants (using coal or oil) and nuclear power plants require cooling in the process of generating electrical power. This cooling generates waste heat that is then discharged into the environment, either directly to the atmosphere by use of cooling towers, or indirectly by first discharging the heat to a water body that then transfers the heat to the atmosphere. If an existing plant already has cooling towers, it is unlikely that the plant will be able to discharge the heat to a water body because of the large capital costs of having two cooling systems. However, many plants do use rivers as the heat sink. The warm water released results in ice suppression that in some instances can be helpful in managing ice problems. Power plants operate either as base load plants, at a more or less constant capacity, or as peaking power plants to supply power at the time of greatest demand. The actual operating characteristics can only be ascertained from the utility companies directly. In Figure 3-38, the waste heat discharge of a power plant on the Mississippi River, 11 kilometers (7 miles) upstream of Lock and Dam No. 15, during January and February of 1980, is shown to illustrate the nature of the output that might be expected. During January of 1980, a large part of the plant was shut down for maintenance, and even after that the plant was not running continuously at full load. As a consequence, the waste heat discharge was variable. Nearly all plants maintain a record of input and output water temperatures, which, along with the cooling water discharge rates, enables calculation of the waste heat discharge. The waste heat discharge is determined from these data according to

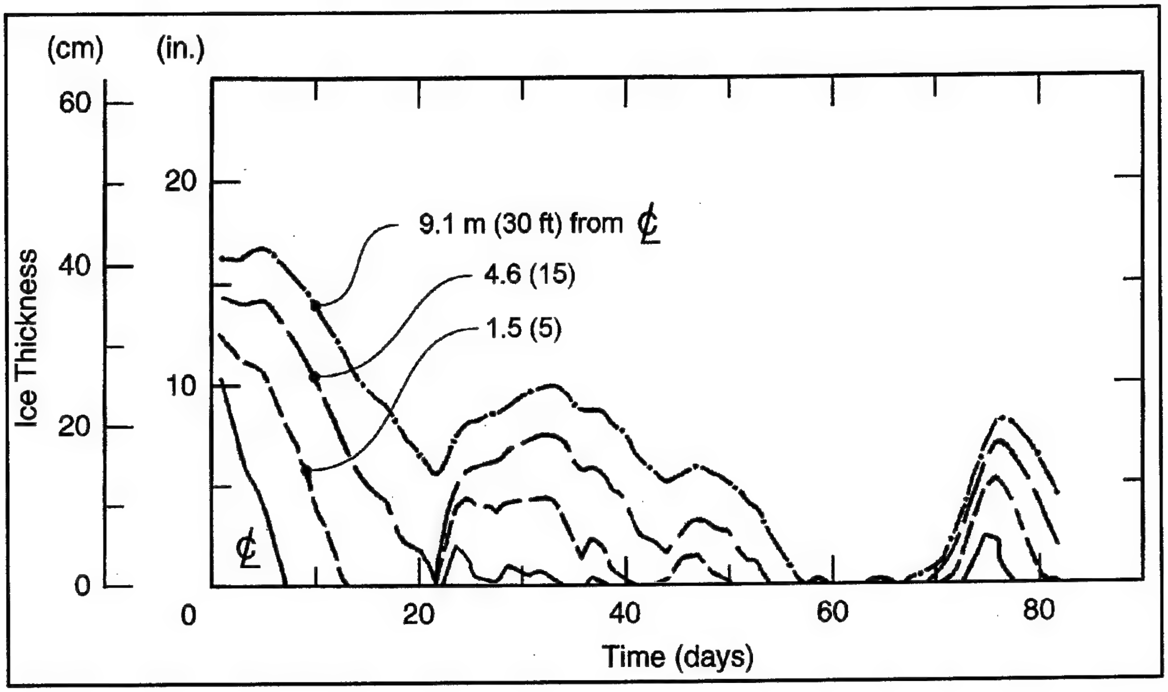


Figure 3-37. Ice thickness, assuming no thermal depletion, Howards Bay, Wisconsin, 1974

$$Q = \gamma C_p N(T_{out} - T_{in} \tag{3-5}$$

where

Q = waste heat release rate, Btu/hr (J/hr)

γ = specific weight of water, 62.4 lb/ft^3 (1000 kg/m^3)

C_p = specific heat of water, 1.0 Btu/lb°F (4.2 × 10^3 J/kg°C)

N = cooling water discharge rate, ft^3/s (m^3/s)

T_{in} = intake cooling water temperature, °F (°C)

T_{out} = outfall cooling water temperature, °F (°C).

As an example, in early February one unit of the plant whose output is shown in Figure 3-38 had an intake temperature of 32°F (0°C), an outfall temperature of 49°F (9.4°C), and a discharge rate of 2.5 m^3/s (89 ft^3/s). Thus, in English units,

$$Q = \left(62.4 \frac{lb}{ft^3}\right)\left(1.0 \frac{Btu}{lb°F}\right)\left(\frac{89 ft^3}{s}\right)(49\,°F - 32\,°F)$$

$$= 94{,}400\,Btu/s = 340 \times 10^6\,Btu/hr, or\ in\ SI units, 99{,}600\,kW.$$

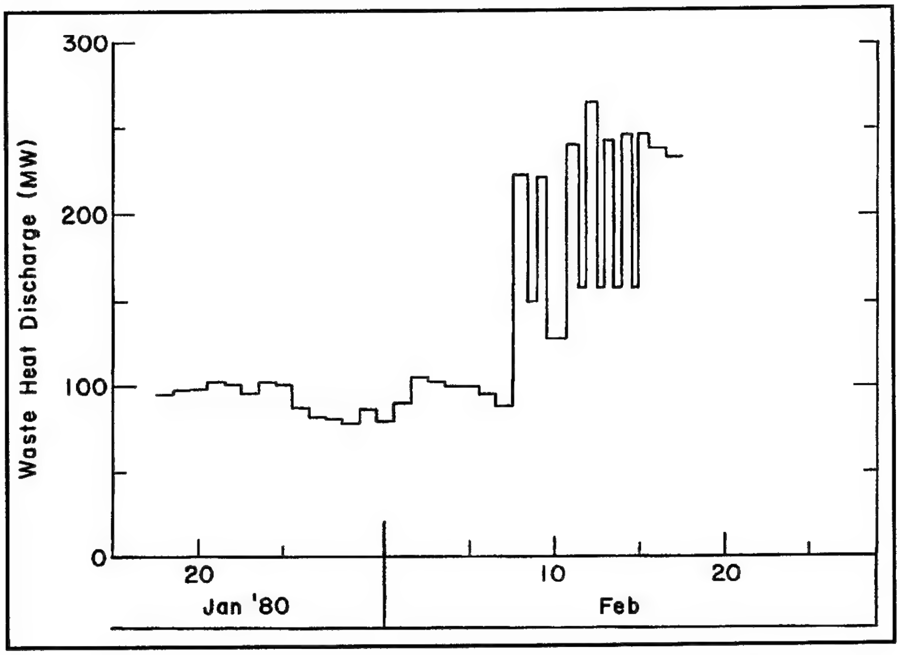


Figure 3-38. Record of waste heat discharge from a power plant that uses Mississippi River water for cooling. *Prior to 8 February, much of the plant was down for maintenance; thereafter, it operated alternately between full and partial load.*

This rate of energy release is greater than the electrical output of the plant, since typically coal and oil plants have 40 percent efficiency, and nuclear plants have even less at about 33 percent. Thus, coal plants discharge as heat energy to the cooling water about 1-1/2 times the amount of electrical energy put out over the transmission lines, and nuclear plants about twice as much. These ratios are useful for quick assessments of ice suppression, as will be discussed below.

(2) In many reservoirs, the water beneath the ice cover is above the freezing point. When this water is released during the winter, it takes some time and distance before it is cooled by the atmosphere down to the freezing point, after which further heat loss results in ice formation. If the warm water release encounters ice before it has cooled to the freezing point, it will melt the ice until the water is at the freezing point. The extent of melting or the distance to cool to the freezing point depends on both the release flow rate and the water temperature. This distance depends also on how cold the atmosphere is. Methods to predict the distance or extent of melting are described below. The biggest uncertainty is the temperature of the reservoir water, which is usually below the 4°C (39°F) temperature of maximum density, and depends on the particular sequence of meteorological conditions at the time of freezeup and the extent of throughflow during the winter. Water released from the bottom of reservoirs will usually be warmer than water released from near the top. Direct measurement of the release water temperature is the most certain way of assessing the flow temperature.

b. Warm water in the context of ice production. In the Pittsburgh District on the Ohio River, there are nine power plants that discharge warm water at a total rate of about 5500 megawatts over a distance of 201 kilometers (125 miles). At –10°C (14°F), the heat loss from open water over this reach is about 15,000 megawatts, so that the warm water reduces ice production by about 37 percent. At –20°C (–4°F), the loss from open water is about 30,000 megawatts, so the warm water reduces ice production by about 18 percent. If the ice is 5 centimeters (2 inches thick), the ice production rate under natural conditions is

equivalent to a heat loss rate of about 7500 megawatts at –10°C (14°F) and 15,000 megawatts at –20°C (–4°F), so the reduced ice production is on the order of 75 percent at –10°C (14°F) and 37 percent at –20°C (–4°F). In the Huntington District there are four power plants on the Ohio River that discharge a total of 4200 megawatts over a distance of 499 km (310 miles). The heat loss from open water over this reach at –10°C (14°F) is on the order of 40,000 megawatts, so the warm water reduces ice production by about 10 percent. At –20°C (–4°F), the reduction is on the order of 5 percent.

(1) Clearly, the magnitudes of warm water discharge are small when compared with the overall energy exchange rates between the river and the atmosphere, and cannot be expected to mitigate ice problems over the entire reaches. Close to the plants, however, the suppression can be significant in affecting local ice conditions.

(2) The fact that large quantities of warm water are discharged into the river does not mean that the water temperatures are excessively high. In fact, in winter the temperatures of the warm water discharges rapidly approach the freezing point. In one observation, for example, 914 meters (3000 feet) downstream of the Riverside Power Plant on the Mississippi River, the highest water temperature in a plume from a 200-megawatt release was only 1.7°C (35°F). However, even small increases in water temperature above the freezing point can stop ice from thickening. As an example, if the air temperature is –20°C (–4°F) and the ice is 15 centimeters (6 inches) thick, the thickening rate is about 4.8 centimeters (1.9 inches) per day, if the water temperature is at the freezing point. If the water velocity is 0.46 m/s (1.5 ft/s) and the temperature is 0.089°C, or 0.089°C above freezing (32.16°F, or 0.16°F above freezing), it will stop the thickening, that is, the heat transferred to the ice from the water exactly equals the heat loss to the atmosphere. Under the same conditions, but with 30.5-centimeter-thick (12-inch-thick) ice, a water temperature of 0.06°C (32.10°F) stops further thickening. Thus, one of the effects of warm water discharge into a cold river is to limit the ice production that otherwise might occur.

3-9. Effects on River Ice of Warm Water Releases

Warm water effects are discussed below by first evaluating natural conditions, and then discussing various modes of heat introduction to the river.

a. Natural conditions. To assess the effects on river ice of a warm water discharge, it is important to appreciate the magnitude of temperatures, natural ice conditions in the river, and the heat losses to the atmosphere that cause ice formation. The water temperatures of rivers more or less follow the average air temperatures through the annual cycle until those temperatures go below the freezing point. At that time, the water, instead of cooling below the freezing point, forms ice in proportion to the heat loss to the atmosphere, and the ice acts as a buffer preventing further temperature decline. Throughout the period of ice cover, water temperatures remain very close to the freezing point, both as a consequence of turbulent mixing, which prevents stratification, and as a consequence of continually flowing past the ice cover, which is a heat sink for the river water. Only in still water or at extremely slow velocities can any significant stratification develop. There is a minor heat gain from energy stored in the bottom sediments during the preceding summer (O'Neill and Ashton 1981), and a minor gain from viscous dissipation or friction in the flow, but these gains are very small relative to the heat losses at the surface. In general, when there are significant amounts of ice present in a river, the assumption that the water temperature is at 0°C (32°F) is very accurate. This is particularly useful when assessing the effects of adding warm water, since all the energy of the warm water is used either to melt ice or is lost to the atmosphere in open water areas.

(1) Ice conditions in a river vary widely from site to site, depending on many factors. These are discussed in other chapters. From the standpoint of the effects of warm water, the ice may be classified as moving or stationary. If the ice is moving, the effect of the warm water is to reduce the volume of ice passed downstream in proportion to the amount of heat discharged. Nearly all the energy discharged into flows with moving ice is used to melt ice. In the case of an intact, stationary ice cover, the waste heat is used to melt the ice or suppress its otherwise natural thickening, as well as being directly lost to the atmosphere in the open-water areas formed by the warm water. In a sense, the open water areas formed in the ice cover act as a short circuit to the atmosphere for some of the waste heat, at least to the extent that the heat transfer rate is greater at larger values of the water-versus-air-temperature difference than would be true for an open-water surface at 0°C (32°F).

(2) This leads directly to the subject of natural heat losses from rivers in winter. Two cases are important—the open-water case and the ice-covered case. In the case of open water, the heat losses may be calculated using detailed energy budget methods, which consider the daily or diurnal variations of long wave radiation gains and losses, short wave radiation gains, sensible heat losses to the air attributable to either free convection (when the air is still) or forced convection (when the air is windy), and evaporation losses. The variables involved include time of year, time of day, latitude, air temperature, humidity, wind speed, and cloud cover. For some studies, such energy budget methods are necessary, but they involve considerable calculation effort, plus field data as input. For many studies a simpler method is adequate for estimates of the effects of warm water discharge. This method consists of simply combining all the energy budget effects into a single heat transfer coefficient applied to the difference between the water temperature and the air temperature (Ashton 1982). The heat loss per unit area of open water surface q_{wa} is then given by

$$q_{wa} = H_{wa}(T_w - T_a) \tag{3-6}$$

where

H_{wa} = heat transfer coefficient

T_w = water temperature

T_a = air temperature.

H_{wa} depends on all the variables that determine the energy budget, but is typically between 15.3 and 25.6 W/m² °C (between 2.7 and 4.5 Btu/hr ft²°F), with the higher values associated with higher wind speeds. As an example, if the air temperature is –12.2°C (10°F) and the water temperature is 0.56°C (33°F) and H_{wa} = 19.9 W/m²°C (3.5 Btu/hr ft²°F), the heat loss in English units is

$$q_{wa} = 3.5\frac{\text{Btu}}{\text{hr ft}^2\,°\text{F}} \times (33 - 10°F) = 80.5\frac{\text{Btu}}{\text{hr ft}^2} = 256\,\frac{\text{W}}{\text{m}^2} \tag{3-7}$$

(3) Once an ice cover is on top of the water, it acts to insulate the water, with the insulation effect increasing as the ice thickens. A snow layer increases the insulation effect even more. And, since the water below is at 0°C (32°F), the heat losses are directly transformed into ice production. A simple layer analysis enables estimates of the heat loss through the ice (and snow) cover. As shown in Figure 3-39, the air temperature is denoted by T_a, the top surface ice temperature by T_s, the bottom surface ice temperature by T_m ,which is always at the melting–freezing temperature of 0°C (32°F). The thermal

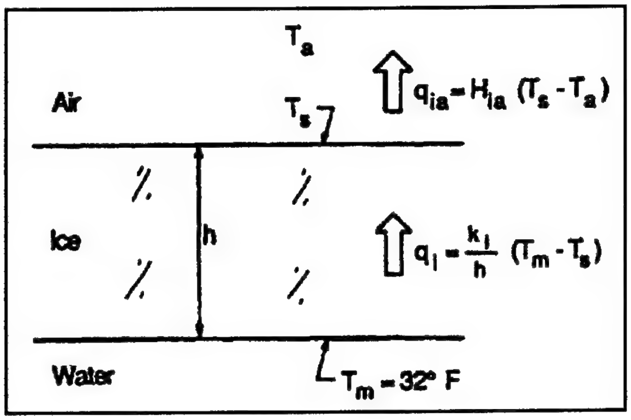


Figure 39. Schematic diagram showing notation and heat transfer equations governing the heat flow from a water body through an ice cover to the atmosphere (32 °F = 0 °C)

conductivity of the ice is denoted by k_i and the ice thickness by h. It is important to note, particularly for thin ice covers, that the top surface temperature is not the same as the air temperature; if it were, there would be negligible heat loss to the atmosphere and no ice thickening. As a first approximation, which is very good for most purposes, the heat flow may be analyzed as a quasi-steady state process such that the temperature profile in the ice varies linearly from T_m to T_s over the thickness of the ice. The heat flow through the ice is then given by

$$q_i = \frac{k_i}{h}(T_m - T_s). \tag{3-8}$$

The heat loss to the atmosphere from the ice q_{ia} can be written similar to that from an open-water surface with T_s substituted for T_w in Equation 3-6 to give

$$q_{ia} = H_{ia}(T_s - T_a) \tag{3-9}$$

The heat flow through the ice equals the heat loss at the surface, so that $q_{ia} = q_i$, which allows T_s to be eliminated between Equations 3-8 and 3-9 and gives

$$q_i = q_{ia} = \frac{T_m - T_a}{\frac{h}{k_i} + \frac{1}{H_{ia}}}. \tag{3-10}$$

This result may be compared to the heat losses from an open-water surface to show the insulating effect of the ice cover. In Figure 3-40, the ratios of heat losses (q_i) through the cover to the open-water losses (q_{wa}) are shown as functions of ice thickness. For the range of heat transfer coefficients usually found, 15 centimeters (6 inches) of ice reduces the heat loss by 50 percent or more.

(4) This heat flux through the ice is also the heat flux upward from the bottom surface, which causes the ice to thicken at the bottom. The thickening rate is inversely proportional to the heat of fusion (L) times the specific weight of ice, so that the thickening rate is given by

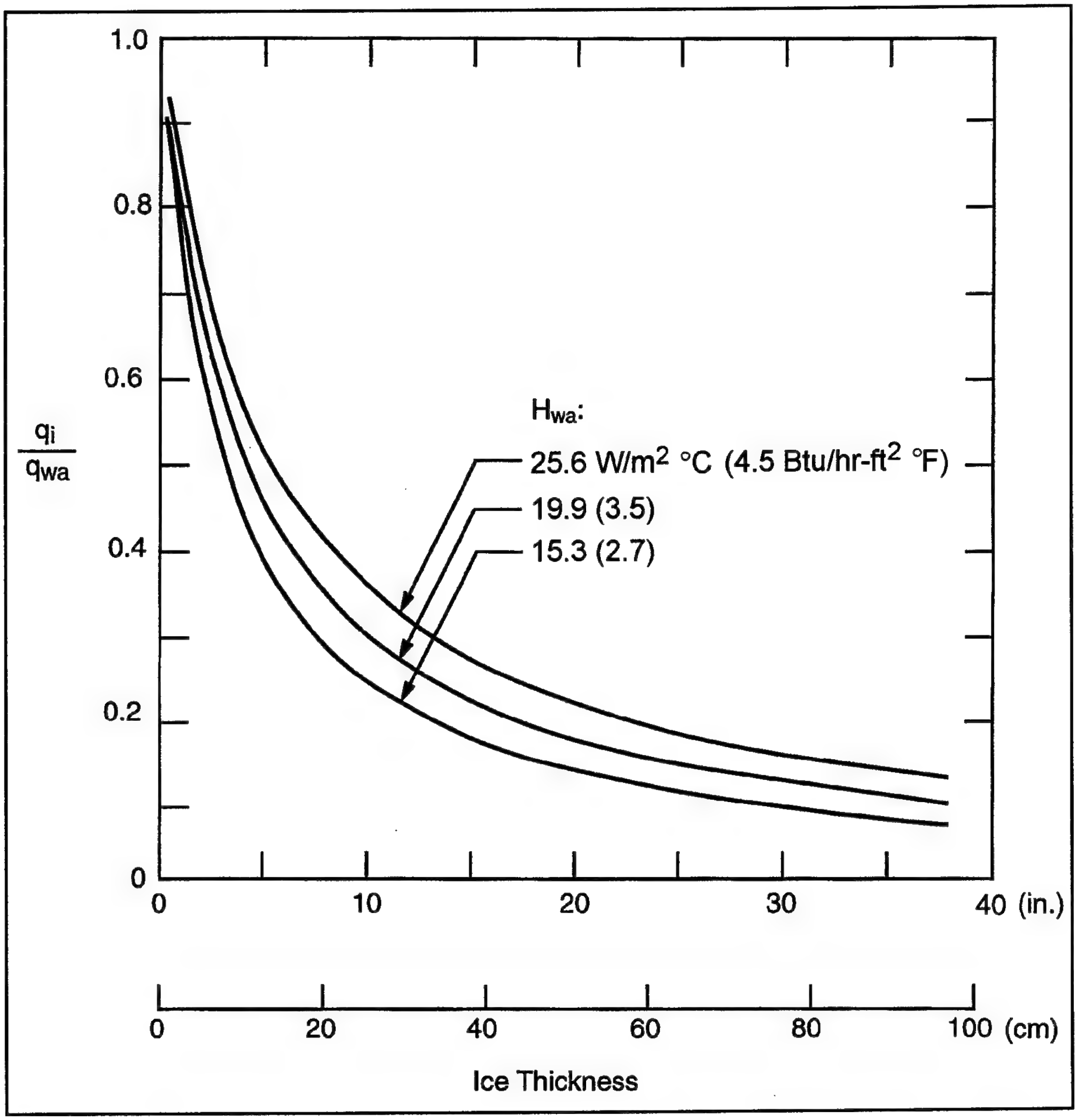


Figure 3-40. Ratio of heat loss through ice cover (q_i) to heat loss from an open-water surface (q_{wa}) versus ice thickness, for three values of the heat transfer coefficient, H_{wa} (or the equivalent H_{ia} for heat transfer from ice to air)

$$\frac{dh}{dt} = \frac{1}{\gamma_i L}\left(\frac{T_m - T_a}{\frac{h}{k_i} + \frac{1}{H_{ia}}}\right) . \tag{3-11}$$

For most practical river ice problems, the specific weight γ_i, the heat of fusion L, and the thermal conductivity k_i may be treated as constants with values for pure ice as follows:

$\gamma_i = 57.2$ lb/ft^3 (916 kg/m^3)

$L = 144$ Btu/lb (3.35×10^5 J/kg)

$k_i = 1.30$ Btu/hr ft °F (2.25 W/m °C).

Using these values gives the thickening rate

$$\frac{dh}{dt} = 0.0029 \left(\frac{T_m - T_a}{0.769h \frac{1}{H_{ia}}} \right) \text{ (ft/day).} \tag{3-12a}$$

In SI units, this becomes

$$\frac{dh}{dt} = 0.00028 \left(\frac{T_m - T_a}{0.444h \frac{1}{H_{ia}}} \right) \text{ (m/day).} \tag{3-12b}$$

As an example, for T_m = 0°C (32°F), T_a = –20.6°C (–5°F) (very cold), h = 0.15 meters (0.5 feet), and H_{ia} = 19.9 W/m^2°C (3.5 Btu/hr ft^2 °F), the thickening rate is 0.049 meters/day (0.16 feet/day) or about 5 centimeters (2 inches) per day. When the ice is 30 cm (1 foot) thick, for the same conditions, the thickening rate drops to 3 centimeters (1.2 inches) per day. Figure 3-41 shows thickening rates to be expected as functions of average daily air temperature and ice thickness, assuming H_{ia} = 19.9 W/m^2°C (3.5 Btu/hr ft^2 °F).

(5) The above calculations overestimate the thickening rate, or rate of ice production, if there is a snow cover on the ice. Typically, the thermal conductivity of the snow cover is about one-tenth that of the ice cover, so it has the insulating effect of ten times its thickness of solid ice.

(6) There are several purposes to the above calculations. First, they may be used to estimate rates of ice production as a function of air temperature and ice thickness. Second, the results of the calculations show that the ice production is greatly reduced as the ice thickens, which, in turn, suggests that the effectiveness of warm water discharged into a river is greatest when the ice is thicker, since a smaller amount of heat is required to stop the growth of the ice cover. Thus, while warm water discharge may not have a great effect in preventing initial ice formation, it may have a significant effect in limiting ice production over significant reaches of the river.

(7) In summary, there are two main effects of warm water released into ice-covered rivers. First, the heat locally suppresses the ice completely and creates open-water areas near the point of release. Second, the heat acts to limit the ice thickness at regions downstream and beneath the ice cover. Both effects may be calculated using methods described below. The effectiveness of the warm water depends a great deal on specific site conditions and the nature of the ice formation that would occur otherwise.

b. Fully mixed releases. The water released from a reservoir is generally above freezing and completely suppresses ice for a certain distance downstream, and partially suppresses the ice further downstream beneath the ice cover. There are methods available (Ashton 1979) to simulate these effects that take into account the unsteady nature of the air temperatures and release rates, but they are too

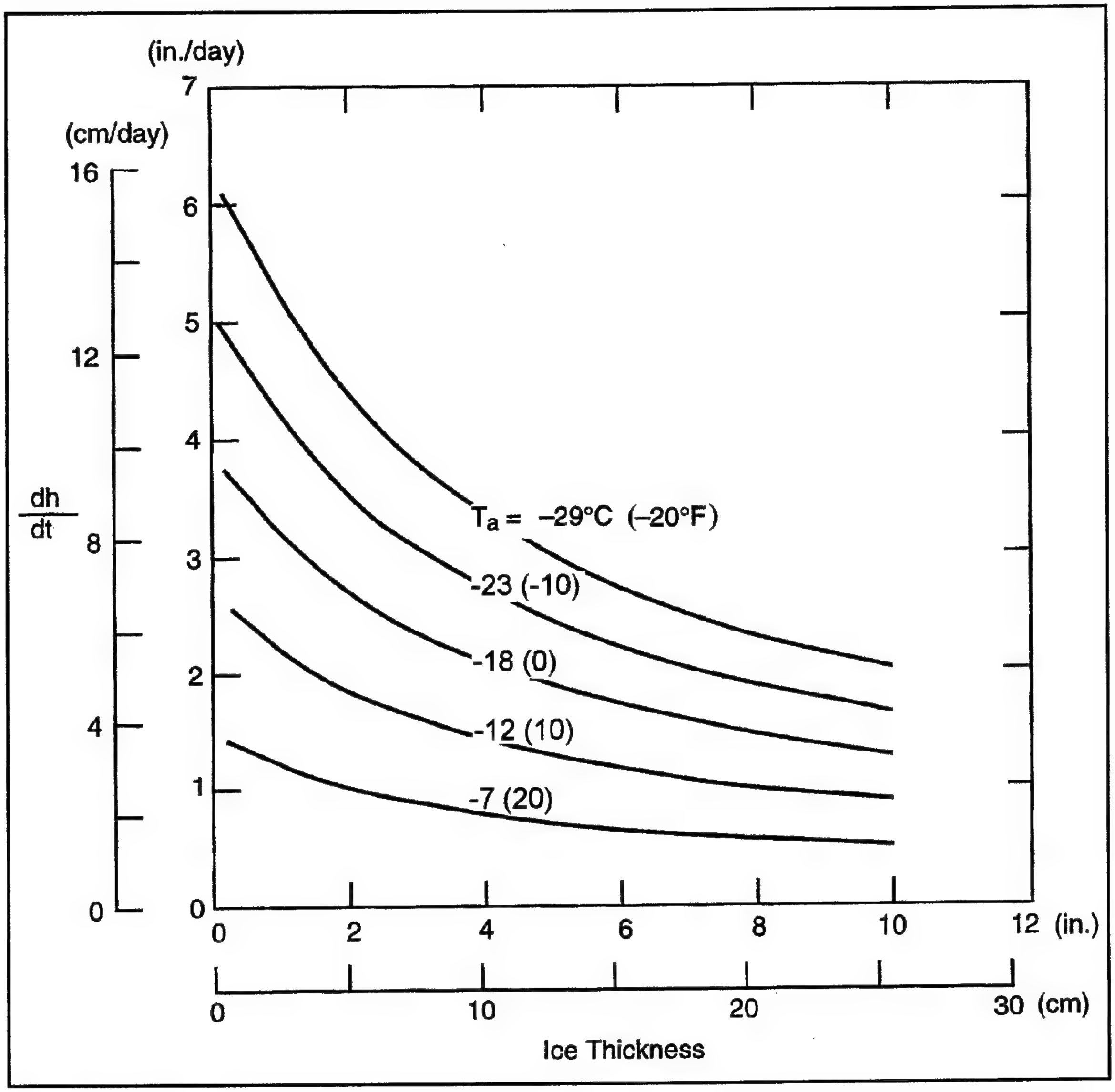


Figure 3-41. Rate of ice thickening versus ice thickness, for five values of average daily air temperature; H_{ia} = 19.9 W/m²°C (3.5 Btu/hr ft² °F) is assumed

detailed for full treatment here. Instead, some steady-state example calculations are presented, as well as some results from unsteady simulations, so as to give an appreciation of whether or not a warm water release causes a significant effect. Occasionally, the effluent from a power plant is diffused uniformly across the receiving river flow, but this is more the exception than the rule. In general this form of release on larger rivers results in insignificant lengths of open water, but a definite suppression of the ice growth (thickness) downstream.

(1) Three example cases are considered: a reservoir discharging 1000 ft³/s (28.3 m³/s) at 36°F (2.2°C) into a river 400 feet wide (122 meters), a reservoir discharging 5000 ft³/s (141.6 m³/s) at 36°F (2.2°C) into a river 500 feet (152 meters) wide, and a very large power plant of nominal capacity of 2400 megawatts discharging 4800 megawatts of waste heat through a diffusing system into a river 2000 feet (610 meters)

wide. As a first approximation, the area of open water, and hence the distance to the upstream edge of the ice cover, can be determined for low air temperatures by estimating the heat transfer coefficient and applying it to the average temperature difference between the water and the air.

(2) Example 1.

(a) *Conditions.*

! Reservoir discharge: 1000 ft^3/s (28.3 m^3/s) at $T_w = 36°F$ (2.2°C)

! Available heat discharge (in English units):

$$Q = \gamma C_p N (T_w - T_m) = 62.4 \times 1.0 \times 1000 \times 3600 \text{ s/hr} \times (36 - 32)$$

$$Q = 899 \times 10^6 \text{ Btu/hr (or } 263 \times 10^6 \text{ W in SI units)}$$

Open-water area: $A = Q/q_{wa} = \dfrac{Q}{H_{wa}(T_w - T_a)}$

! Width of open water : $W = 400$ feet (122 meters)

! Length of open water : $L = A/W$

! For $H_{wa} = 3.5$ Btu/hr ft²°F (19.9 W/m²°C):

T_a °F (°C)	$T_w - T_a$ °F (°C)	A ft² (m²)	L ft (m)
20 (–6.7)	12 (6.7)	21.4×10^6 (19.9×10^5)	53,500 (16,300)
10 (–12.2)	22 (12.2)	11.7×10^6 (10.9×10^5)	29,200 (8,900)
0 (–17.8)	32 (17.8)	8.0×10^6 (7.4×10^5)	20,100 (6,100)
–10 (–23.3)	42 (23.3)	6.1×10^6 (5.7×10^5)	15,300 (4,700)

(b) *Discussion.* This reservoir release maintains open water in the river downstream a distance up to 10 miles (16 kilometers) when the weather is mild in winter, and the distance shortens to a little less than 3 miles (5 kilometers) when the weather is very cold (note that for this case –10°F [–23.3°C] is the average daily temperature and not the extreme overnight low). The heat release is equivalent to 240 megawatts, which is about the rate of heat released from a fossil-fueled power plant of nominal capacity of 160 megawatts. The discharge over 2 months adds up to 120,000 acre-ft (1.48×10^8 m^3), and requires a significant reservoir if it is to have that capacity of warm water at the beginning of the ice-covered period.

(3) Example 2.

(a) *Conditions.*

! Reservoir discharge: 5000 ft^3/s (141.6 m^3/s) at $T_w = 36°F$ (2.2°C)
! Available heat discharge (in English units):

$Q = \gamma C_p N (T_w - T_m) = 62.4 \times 1.0 \times 5000 \times 3600$ s/hr $\times (36 - 32)$

$Q = 4490 \times 10^6$ Btu/hr (or 1316×10^6 W in SI units)

! Open-water area: $A = Q/q_{wa} = \dfrac{Q}{H_{wa}(T_w - T_a)}$

! Width of open water: W = 500 feet (152 meters)

! Length of open water: $L = A/W$

! For H_{wa} = 3.5 Btu/hr ft² °F (19.9 W/m²°C):

T_a °F (°C)	$T_w - T_a$ °F (°C)	A ft² (m²)	L ft (m)
20 (–6.7)	12 (6.7)	107×10^6 (99.4×10^5)	214,000 (65,200)
10 (–12.2)	22 (12.2)	58×10^6 (53.9×10^5)	117,000 (35,700)
0 (–17.8)	32 (17.8)	40×10^6 (37.2×10^5)	80,000 (24,400)
–10 (–23.3)	42 (23.3)	31×10^6 (28.8×10^5)	61,000 (18,600)

(b) *Discussion.* This is a large reservoir release with open water about 11.6 miles (18.7 kilometers) downstream even at –10°F (–23.3°C) air temperature. The heat release is equivalent to 1200 megawatts, which is about the heat released from a fossil-fueled power plant of 800-megawatts capacity. The discharge over 2 months is 600,000 acre-ft (7.4×10^8 m³).

(4) Example 3.

(a) *Conditions.* A large power plant of nominal capacity 2400 megawatts is discharging 4800 megawatts through a diffusing system into a river 610 meters (2000 feet) wide. Temperature rise in the river depends on its flow, but under the simplified assumptions used here, the open-water area can be calculated approximately without that knowledge, since it is based on the required water surface area to remove the heat content. This surface area depends on the temperature difference between the water and the air, and the water temperature will be very near 32°F (0°C).

! Available heat discharge:

$$Q = 4800\,MW \times \frac{10^6\,Btu/hr}{0.293\,MW}$$

$Q = 16{,}400 \times 10^6$ Btu/hr

! Open-water area: $A = Q/q_{wa} = \dfrac{Q}{H_{wa}(T_q - T_a)}$

! Width of open water: W = 2000 feet (610 meters)

! Length of open water: $L = A/W$

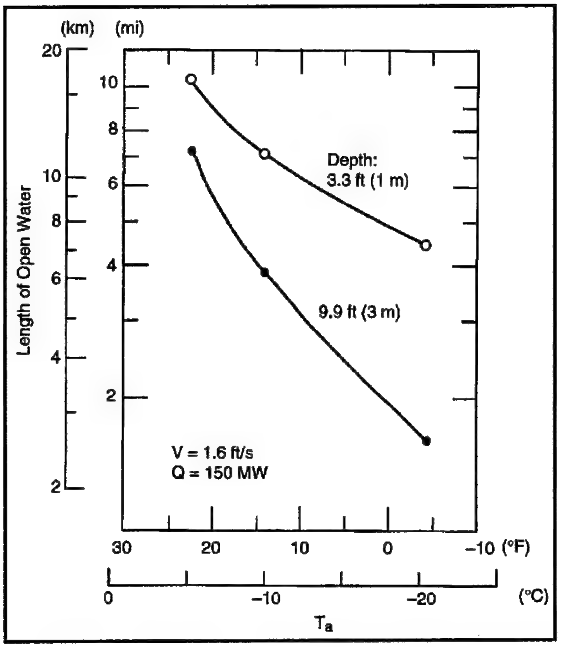
! For H_{wa} = 3.5 Btu/hr ft^2 °F (19.9 W/m^2°C), and
$T_w - T_a$ = 32°F (0°C) – T_a:

T_a °F (°C)	$T_w - T_a$ °F (°C)	A ft^2 (m^2)	L ft (m)	L mi (km)
20 (–6.7)	12 (6.7)	390 × 10^6 (362 × 10^5)	195,000 (65,200)	37 (60)
10 (–12.2)	22 (12.2)	213 × 10^6 (198 × 10^5)	106,000 (35,700)	20 (32)
0 (–17.8)	32 (17.8)	146 × 10^6 (136 × 10^5)	73,000 (24,400)	14 (23)
–10 (–23.3)	42 (23.3)	111 × 10^6 (103 × 10^5)	56,000 (18,600)	11 (18)

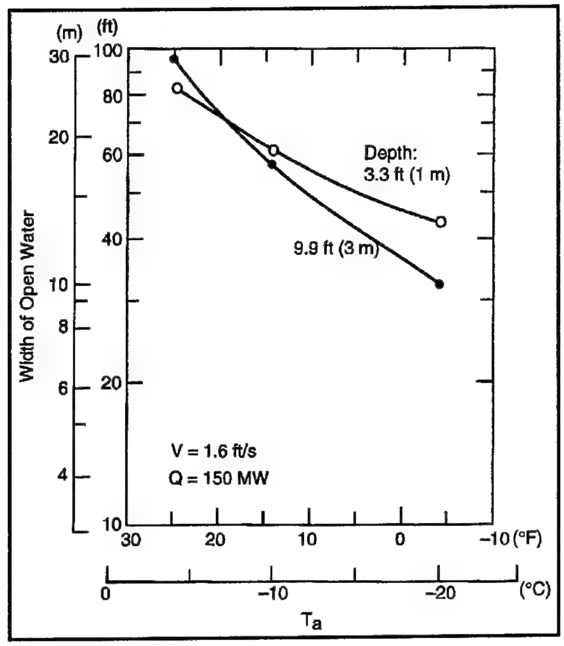
(b) *Discussion.* This is a very large power plant and a very large river. The effect on the ice is open water for many miles or kilometers downstream when the air is mildly cool, but only 16 to 24 kilometers (10 to 15 miles) when the air temperatures are around 0°F (–17.8°C). The simplified assumption, namely that the open-water area is based only on the area required to remove the heat added, is probably not very accurate here, since the complete mixing by the diffuser probably results in water temperatures sufficiently close to freezing that ice will form on top of the slightly warm water if the flow is not too fast. For such a case, a more detailed analysis would be needed. If skim ice forms, however, the warm water still prevents the ice from thickening as much as it would without the addition of heat. Note also that we did not need to know the velocity of the flow or the depth, but merely needed to assume that the flow was fast enough to mix the warm water, and carry it downstream.

c. Side channel releases. The most usual method of disposing of a power plant's waste heat to a river is to release it directly at the side of the river. This case is more difficult to analyze because now the rate of transverse mixing of the warm water plume across the river must be considered. As a general rule, the open-water area resulting from a side channel release is quite narrow, on the order of 15 to 30 meters (50 to 100 feet), but very long, on the order of miles or kilometers. While some of the heat is transferred directly to the atmosphere through the open-water area, a significant amount of the heat is transferred to the bottom of the adjacent ice cover and to the bottom of the ice cover downstream of the end of the open water. From the standpoint of maximum decrease of the volume of ice that would be produced in the river without waste heat, this is the most effective use of the waste heat since, once under the ice cover, nearly all of the heat is used to retard ice thickening or to melt it. Simulations are available that enable estimates of the lengths and widths of open water and the amount of ice suppression that results beyond the open water, but they depend on the amount of heat released, the flow velocity, air temperature, depth of the river, and the mixing characteristics of the river. For straight reaches of river, the simulations seem to yield reasonable estimates of open-water extents.

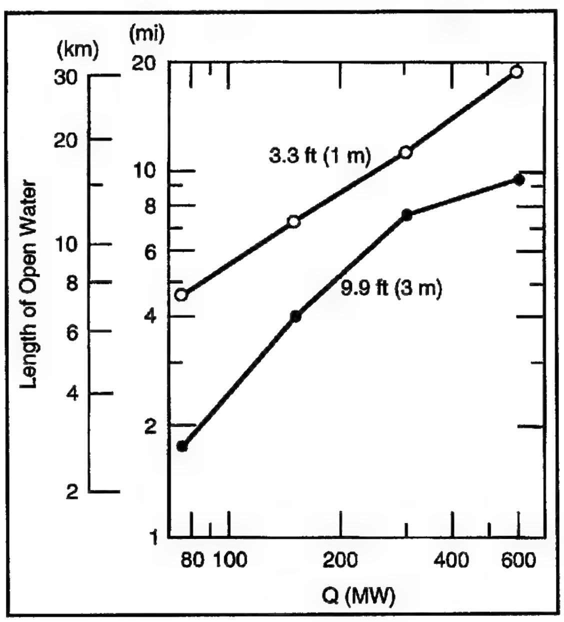
(1) Figure 3-42 shows parametric plots of the lengths and widths of open water that may be expected from a side channel release of warm water into rivers of 1- and 3-meter (3.3- and 9.9-foot) depths, with flow velocities of 0.5 m/s (1.6 ft/s), as functions of air temperature and rates of heat release. These figures are useful for gaining an appreciation of the nature of the ice suppression. Figure 3-42a shows



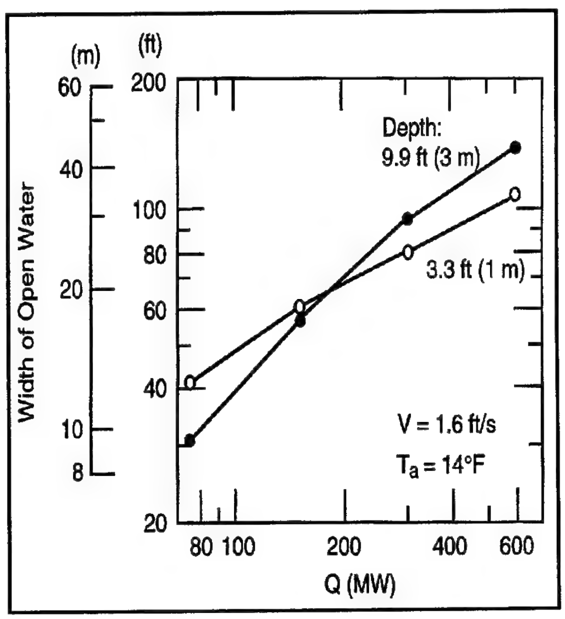
a. Length versus air temperature, heat discharge fixed at 150 megawatts



b. Width versus air temperature, heat discharge fixed at 150 megawatts



c. Length versus heat discharge rate, air temperature fixed at -10 °C (14 °F)



d. Width versus heat discharge rate, air temperature fixed at -10 °C (14 °F)

Figure 3-42. Length and width of open water resulting from side channel release of warm water into a river of either 1- or 3-meter (3.3- or 9.9-foot) depth, as functions of air temperature and heat discharge rate. In all cases the flow velocity is 0.5 m/s (1.6 ft/s)

that, as the air gets colder, the length of open water decreases significantly. The length of open water is also much shorter for the deeper river than for the shallower river. Figure 3-42b shows that the width of open water is little affected by the depth, but of course it is narrower at lower air temperatures. Figures 3-42c and 3-42d show the effect of different rates of heat release on the lengths and widths of open water. As expected, both the length and width increase with increasing warm water discharge.

(2) Not apparent from the various plots of Figure 3-42 are the relative amounts of heat from the warm water that are transferred directly to the atmosphere through the open water or that are transferred to the underside of the ice. Less than 30 percent of the heat is transferred through the open water to the air in all cases. This means that 70 percent of the heat is transferred to the ice cover, and either retards thickening or causes thinning of the ice. This effect of the waste heat may extend for many miles or kilometers further downstream, beyond the end of the open-water reach. These effects have been simulated by numerical analysis but are too complex to be described quantitatively here, since the effects vary from site to site. Some general statements can be made, however. The rate of heat transfer to the bottom of the ice cover is more or less proportional to the product of the velocity and the amount by which the water temperature is above freezing. Even temperature differences as small as 0.06°C (0.1°F) have effects that are important, so that any field measurements must use accurate thermometers. The deeper the water is, the further downstream the waste heat will affect the ice. For depths on the order of 1 meter (3 feet), the warm water will have cooled to very near freezing in about 5 kilometers (3 miles), while for depths of about 3.7 meters (12 feet), the effect will extend for as far as 16 kilometers (10 miles).

d. Mid-channel releases. Rarely is waste heat from a power plant discharged in the middle of a river. If it were, the effects would be similar to a side channel release and result in a long, narrow open- water stretch. The open water would be wider than a side channel release but shorter because the warm water now mixes and spreads on both sides of the thermal plume, rather than only on one side. There may be cases where it would be desirable from an ice management viewpoint to release an existing source of warm water other than at the side. Before doing this, a simulation of the effects should be made to estimate whether the ice suppression would be effective at the particular site.

3-10. References

a. Required publications.
None.

b. Related publications.

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Chapter 4
Hydraulic Computations and Modeling of Ice-Covered Rivers

4-1. Introduction

This chapter describes the general concepts for numerical modeling of the hydraulics of ice-covered channels and contains background material and the equations used. The calculation of the hydraulics of rivers for open water conditions (i.e., water-surface profiles) has a long history and well established procedures. One of the complications imposed by ice on rivers is the difficulty of calculating the hydraulic parameters of interest when the flow is affected by an ice cover or an ice jam. Section I of this chapter presents the general principles and equations for modeling river ice covers. Over 30 years ago, the Corps of Engineers' Hydrologic Engineering Center (HEC) formulated the first version of the program known as HEC-2 for calculating the hydraulics of open-channel flow (U.S. Army 1990). In an effort to model the effect of an ice cover, a utility program called ICETHK was developed at CRREL to be used in conjunction with HEC-2. Section II of this chapter describes the ICETHK model. More recently, the HEC-RAS model (for River Analysis System) was developed by the Hydrologic Engineering Center as a replacement for HEC-2. HEC and CRREL collaborated to include river ice as an integral part of the structure of the new model. As such, HEC-RAS overcomes several limitations that exist in ICETHK, and it applies to a wider variety of river ice situations. The ice-handling characteristics of HEC-RAS are described in Section III.

a. ICETHK. ICETHK is a useful engineering tool, since many flood studies and hydraulic design projects require the calculation of ice-affected stages. Before the development of ICETHK, the calculation of ice-affected backwater profiles using HEC-2 was painstaking, requiring many iterations. The model has two strong points. First, ICETHK is used in conjunction with HEC-2, the most commonly used backwater model in the United States, and river geometry data in the HEC-2 format are widely available. Second, ICETHK is designed to help the user understand ice jam processes and is relatively easy to use. The original ICETHK model has been supplanted by an improved ice routine in HEC-RAS, but it is described in this chapter for those who may continue to find it useful and because of its strong association with the well-established HEC-2 model.

b. HEC-RAS. The HEC-RAS model of river hydraulics contains code that enables the user to model ice-covered channels at two levels. The first level applies to an ice cover with known geometry. In this case, the user specifies the ice cover thickness and roughness at each cross section. Different ice cover thicknesses and roughnesses can be specified for the main channel and for each overbank, and both the thickness and roughness can vary along the channel. The second level addresses a wide-river ice jam. In this case, the ice thickness is determined by an ice jam force balance. The ice jam can be confined to the main channel or can include both the main channel and the overbanks. The material properties of the wide-river jam can be selected by the user and can vary from cross section to cross section. The user can specify the hydraulic roughness of the ice jam, or HEC-RAS will estimate the hydraulic roughness on the basis of empirical data.

Section I
Modeling River Ice Covers

4-2. General

The common formation of ice covers on rivers during the cold winter months arises in a variety of ways. How an ice cover forms depends on the channel flow conditions and the amount and type of ice generated. In most cases, river ice covers float in hydrostatic equilibrium because they react both elastically and plastically (the plastic response being termed *creep*) to changes in water level. The thickness and roughness of ice covers can vary significantly along the channel and even across the channel. A stationary, floating ice cover creates an additional fixed boundary with an associated hydraulic roughness. An ice cover also makes a portion of the channel cross-sectional area unavailable for flow, i.e., that part occupied by the ice. The net result is generally to reduce the channel conveyance, largely by increasing the wetted perimeter and reducing the hydraulic radius of a channel, but also by modifying the effective channel roughness and reducing the channel flow area.

4-3. Modeling Ice Covers with Known Geometry

The conveyance of a channel or any subdivision of an ice-covered channel, K_i, can be estimated using the Manning equation:

$$K_i = \frac{1.486}{n_c} A_i R_i^{2/3} \tag{4-1}$$

where

n_c = composite roughness

A_i = flow area beneath the ice cover

R_i = hydraulic radius modified to account for the presence of ice.

The composite roughness of an ice-covered river channel can be estimated using the Belokon-Sabaneev equation as

$$n_c = \left(\frac{n_b^{3/2} + n_i^{3/2}}{2} \right)^{2/3} \tag{4-2}$$

where

n_b = roughness value for the bed

n_i = roughness value for the ice.

The hydraulic radius of an ice-covered channel is found as

$$R_i = \frac{A_i}{P_b + B_i} \tag{4-3}$$

where

P_b = wetted perimeter associated with the channel bottom and sideslopes

B_i = width of the underside of the ice cover.

It is interesting to estimate the influence that an ice cover can have on the channel conveyance. For example, if a channel is roughly rectangular in shape and much wider than it is deep, then its hydraulic radius will be approximately cut in half by the presence of an ice cover. Assuming that the flow area remains constant, we see that the addition of an ice cover, having a roughness equivalent to the bed roughness, reduces conveyance by 37 percent.

4-4. Modeling Wide-River Ice Jams

The wide-river ice jam is probably the most common type of river ice jam (Figure 4-1). In this type, all stresses acting on the jam are ultimately transmitted to the channel banks. The stresses are estimated using the ice-jam force balance equation:

$$\frac{d\,\bar{\sigma}_x t}{dx} + \frac{2\tau_b t}{B} = \rho' g S_w + \tau_i \tag{4-4}$$

where

$\bar{\sigma}_x$ = longitudinal stress (along stream direction)

t = the accumulation thickness

τ_b = shear resistance of the banks

B = accumulation width

ρ' = ice density

g = acceleration of gravity

S_w = water surface slope

τ_i = shear stress applied to the underside of the ice by the flowing water.

This equation balances changes in the longitudinal stress in the ice cover and the stress acting on the banks with the two external forces acting on the jam, namely the gravitational force attributable to the slope of the water surface and the shear stress of the flowing water on the jam underside.

a. Assumptions. Two assumptions are implicit in this force balance equation: that $\bar{\sigma}_x$, t, and τ_i are constant across the width, and that none of the longitudinal stress is transferred to the channel banks

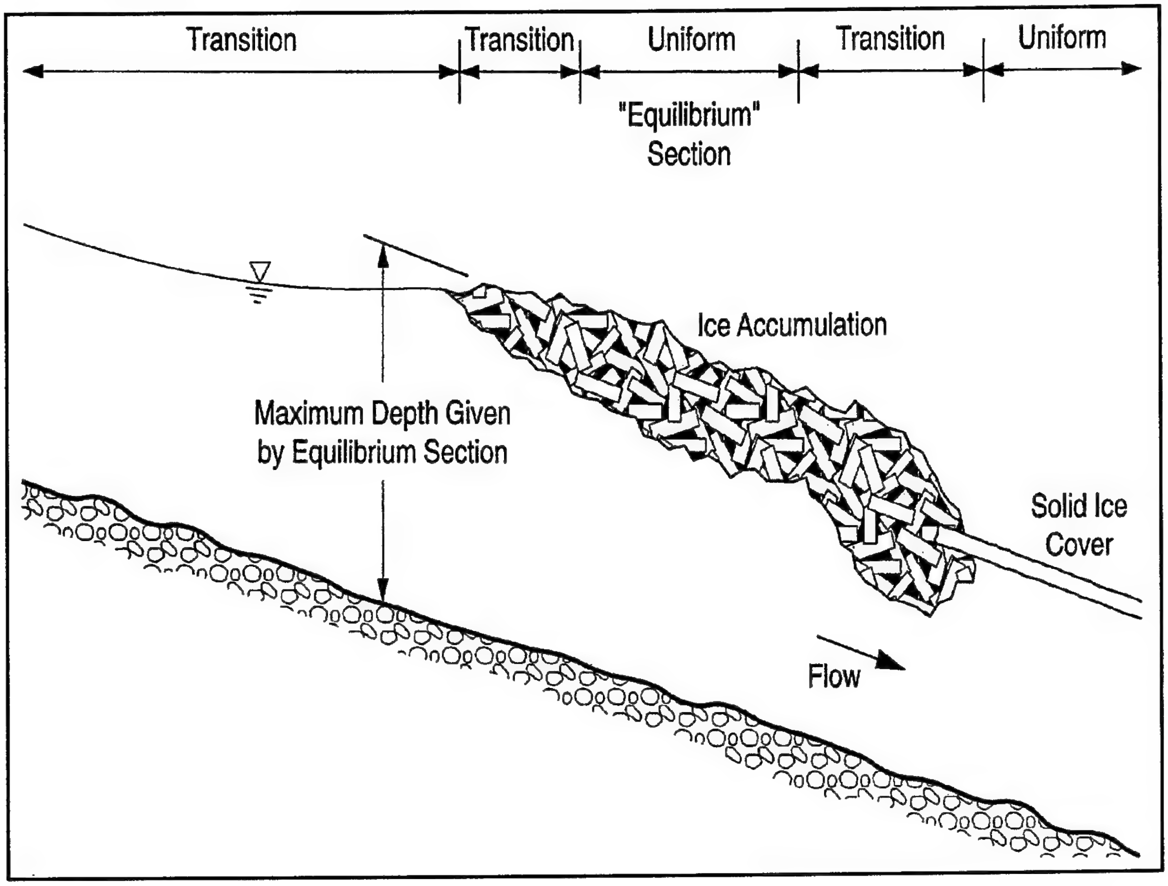

Figure 4-1. Schematic profile of a wide-river ice jam. *Note that the ICETHK model applies to the "equilibrium section" of the jam where ice thickness and flow are relatively uniform. HEC-RAS applies to the entire jam except grounded portions, if any*

through changes in stream width or horizontal bends in the plan form of the river. In addition, the stresses acting on the jam can be related to the mean vertical stress using the passive pressure concept from soil mechanics, and the mean vertical stress results only from the hydrostatic forces acting in the vertical direction. In the present case, we also assume that there is no cohesion between individual pieces of ice, a reasonable assumption for ice jams formed during river ice breakup.

(1) In this light, the vertical stress, $\bar{\sigma}_z$, is

$$\bar{\sigma}_z = \gamma_e t \tag{4-5a}$$

in which

$$\gamma_e = \frac{1}{2} \rho' g \ (1 - s) \ (1 - e) \tag{4-5b}$$

where

e = ice jam porosity (assumed to be the same above and below the water surface)

s = specific gravity of ice.

(2) The longitudinal stress is then

$$\bar{\sigma}_x = k_x\,\bar{\sigma}_z \tag{4-6}$$

where

$k_x = \tan^2 (45° + \phi/2)$

ϕ = angle of internal friction of the ice jam.

(3) The lateral stress perpendicular to the banks can also be related to the longitudinal stress as

$$\bar{\sigma}_y = k_1\,\bar{\sigma}_x \tag{4-7}$$

where

k_1 = coefficient of lateral thrust.

(4) Finally, the shear stress acting on the bank can be related to the lateral stress

$$\tau_b = k_o\,\bar{\sigma}_y \tag{4-8}$$

where

$k_o = \tan\phi$.

b. Reformulation of the force balance equation. Using the above expressions, we can restate the ice-jam force balance as

$$\frac{dt}{dx} = \frac{1}{2\,k_x\,\gamma_e}\left(\rho' g\,S_w + \frac{\tau_i}{t}\right)\,\frac{k_o k_1\,t}{B} = F \tag{4-9}$$

where

F = shorthand description of the force balance equation.

4-5. Roughness of the Ice Accumulation

Ice roughness can be calculated as a function of ice thickness or as a function of ice piece size. Existing field data show that thick jams are typically made up of larger ice pieces and are hydraulically rougher than thin jams. Relationships based on Nezhikhovskiy's (1964) data relate Manning's n for the ice cover to the ice accumulation thickness. The relationships take the form of a similar equation by Beltaos (1983). Nezhikhovskiy's data were measured in wide canals, 2–3 meters (6.6–9.8 feet deep), for ice floes, dense slush, and loose slush.

a. Thick breakup jams. For breakup ice jams with ice accumulations greater than 0.46 meters (1.5 feet) thick:

$$n_i = 0.0588\left(\frac{H}{2}\right)^{-0.23} t_i^{0.40} = 0.0690\ H^{-0.23}\, t_i^{0.40} \tag{4-10}$$

where

H = total water depth

t_i = measured thickness of the ice accumulation.

b. Thin breakup jams. A second relationship for breakup ice jams applies to ice accumulations less than 0.46 meters (1.5 feet) thick:

$$n_i = 0.0506\left(\frac{H}{2}\right)^{-0.23} t_i^{0.77} = 0.0593\ H^{-0.23}\, t_i^{0.77} \tag{4-11}$$

c. Freezeup jams. A third relationship predicts the roughness of a freezeup ice jam:

$$n_i = 0.0249\left(\frac{H}{2}\right)^{-0.23} t_i^{0.54} = 0.0292\ H^{-0.23}\, t_i^{0.54} \tag{4-12}$$

d. Roughness summary. Nezhikhovskiy's data and the curves produced by these three equations are plotted in Figure 4-2.

4-6. Limitations of Ice Modeling

Although there are a number of limitations that arise from the assumptions required to solve the ice-jam force balance in practical situations, the models have produced good results in a number of applications. There are two general classes of limitations: those associated with the circumstances of the jam formation, and those describing the material properties of the jam.

a. Limitations attributable to circumstances of jam formation. Both HEC-RAS and ICETHK assume one-dimensional, gradually varied, steady flow. This may be in error when the ice jam formed during a surge or other transient flow event. However, the extent to which the ice jam is influenced by

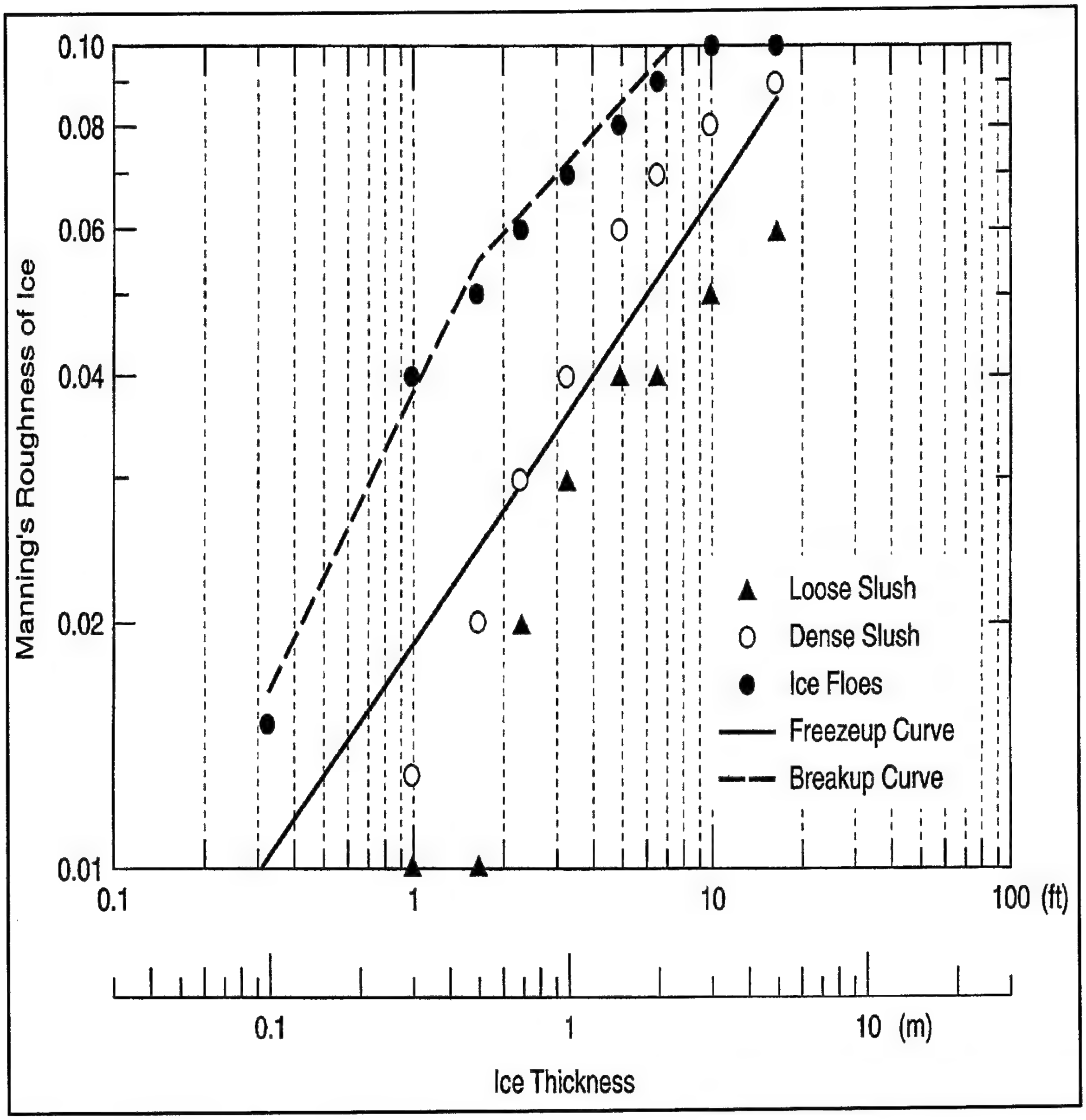

Figure 4-2. Nezhikovskiy's ice roughness values. *The data are plotted in log-log format with the ice-thickness versus ice-roughness relationships used in the ICETHK model*

the unsteady flow cannot be estimated at this time. Neither HEC-RAS nor ICETHK can estimate where an ice jam will occur. This information must be entered by the user.

b. Limitations attributable to jam material properties description. The collection of ice floes that make up the jam are assumed to be a granular material with known properties. The determination of these properties requires that the ice jam be floating in hydrostatic equilibrium. The result is that grounded ice jams, where the ice jam is resting fully or partially on the channel bottom, cannot be well described by this approach. This may have the largest influence at the downstream end or "toe" of the jam in the calculated

results. However, it has generally been found that this description produces "reasonable" results in the toe area.

Section II
The ICETHK Model

4-7. General

ICETHK is an ice utility program that is used in conjunction the HEC-2 backwater model to simulate an equilibrium ice jam profile (Tuthill et al. 1998). ICETHK uses the results of hydraulic calculations from HEC-2, with an ice cover, to produce new estimates of ice thickness and ice roughness for the reach of river being modeled. HEC-2 is then used to recalculate the hydraulic conditions with the updated ice values from the previous ICETHK run. The HEC-2 and ICETHK iteration cycles continue until the change in ice thickness between successive iterations is acceptably small.

4-8. Ice Covers with Known Geometry

The utility program ICETHK cannot be used to model ice covers with known geometry (i.e., the ice cover thickness and roughness are known at every cross section). If the ice cover geometry is known, this information can be entered into HEC-2 directly using the IC card. The reader is referred to the HEC-2 Manual (U.S. Army 1990) for this information.

4-9. Equilibrium Ice Jam Theory and ICETHK

a. Definition of an equilibrium ice jam. ICETHK treats each reach between adjacent cross sections as individual equilibrium reaches. The equilibrium form of Equation 4-9 above can be found by setting the differential term with respect to x, the longitudinal distance, to zero. Equilibrium ice jam theory assumes that the downstream forces on the ice cover are resisted by the accumulation's internal strength and bank shear. In this case it is assumed that the downstream forces are the water drag on the ice accumulation's underside and the downstream component of the ice accumulation's weight. The ice accumulation's ability to transfer these downstream forces to the banks depends on its internal strength and thickness, and the model's governing equations determine the minimum ice thickness at which this force balance can occur.

b. Ice thickness calculation. ICETHK calculates ice thickness by three processes: juxtaposition, wide-river jam, and thinning by erosion. In this manual, only the wide-river ice jam will be discussed. In this case the wide-river jam can be simplified to a quadratic algebraic equation to reflect the ice jam forces in an equilibrium reach.

$$\mu\left(1 - \frac{\rho'}{\rho}\right)\rho' g t^2 - (g\rho' S_f B - 2_{C_i})t - \tau_i B = 0 \tag{4-13}$$

where

μ = coefficient related to the internal strength of the accumulation, ranging from 0.8 to 1.3

ρ, ρ' = densities of water and ice, respectively

g = acceleration due to gravity

t = thickness of the ice accumulation

S_f = friction slope (assumed equal to the water surface slope)

B = channel width at bottom of ice cover

C_i = cohesion factor for ice can range from zero for breakup jams to 958 Pa (20 lb/ft^2) for freezeup jams

τ_i = shear force on underside of accumulation, approximated by $\rho\, g(y_i/2)\, S_f$, where y_i = under-ice depth.

This quadratic equation can be solved directly.

4-10. Ice in Overbank Areas

Once flow depth in the floodplain reaches a threshold value, ice thickness in the overbank areas is determined by the same steps and equations as the channel ice thickness. The threshold floodplain depth is defined by a specified factor times the ice thickness before breakup. The use of the same calculation method to calculate ice thickness in the overbank area (i.e., the same method as is used for the main channel area) relies on the assumption that the ice-on-ice shear between the channel and floodplain ice is approximately equivalent to the bank shear of a jam remaining in the channel.

4-11. Structure and Operation of ICETHK

ICETHK is designed as a utility program for HEC-2. Figure 4-3 shows the program's overall structure and the interaction between ICETHK and HEC-2. Square-cornered boxes signify ICETHK programs and sub-programs, while boxes with rounded corners indicate external input and output files. Overall, the structure is fairly simple: ICETHK reads hydraulic data from a HEC-2 output file. Then the thickness and roughness of the equilibrium ice accumulation are calculated. If water current velocity is greater than the threshold velocity for thinning, thinning of the ice accumulation is calculated, as previously described. If juxtaposition is possible, thickening from juxtaposition is found. The shoving thickness of the accumulation is then calculated, and the greater of the shoving and juxtaposition thicknesses is selected. The thickness of the initial (parent) ice cover is used as a minimum. This means that the cover cannot thin beyond the parent ice thickness. It also means that, if a solution is not possible by juxtaposition or shoving, the parent ice thickness will be used. Next, the ice roughness is calculated as a function of accumulation thickness. If floodplain flow depth is greater than a user-defined threshold value, the process described for the main channel is repeated to calculate ice thickness in the overbank areas. Finally, the resulting ice data are inserted into the original HEC-2 input file, creating a new input file.

Section III
The HEC-RAS Model

4-12. General

HEC-RAS allows the user to model ice-covered channels at two levels. The first level is an ice cover with known geometry. In this case, the user specifies the ice cover thickness and roughness at each cross

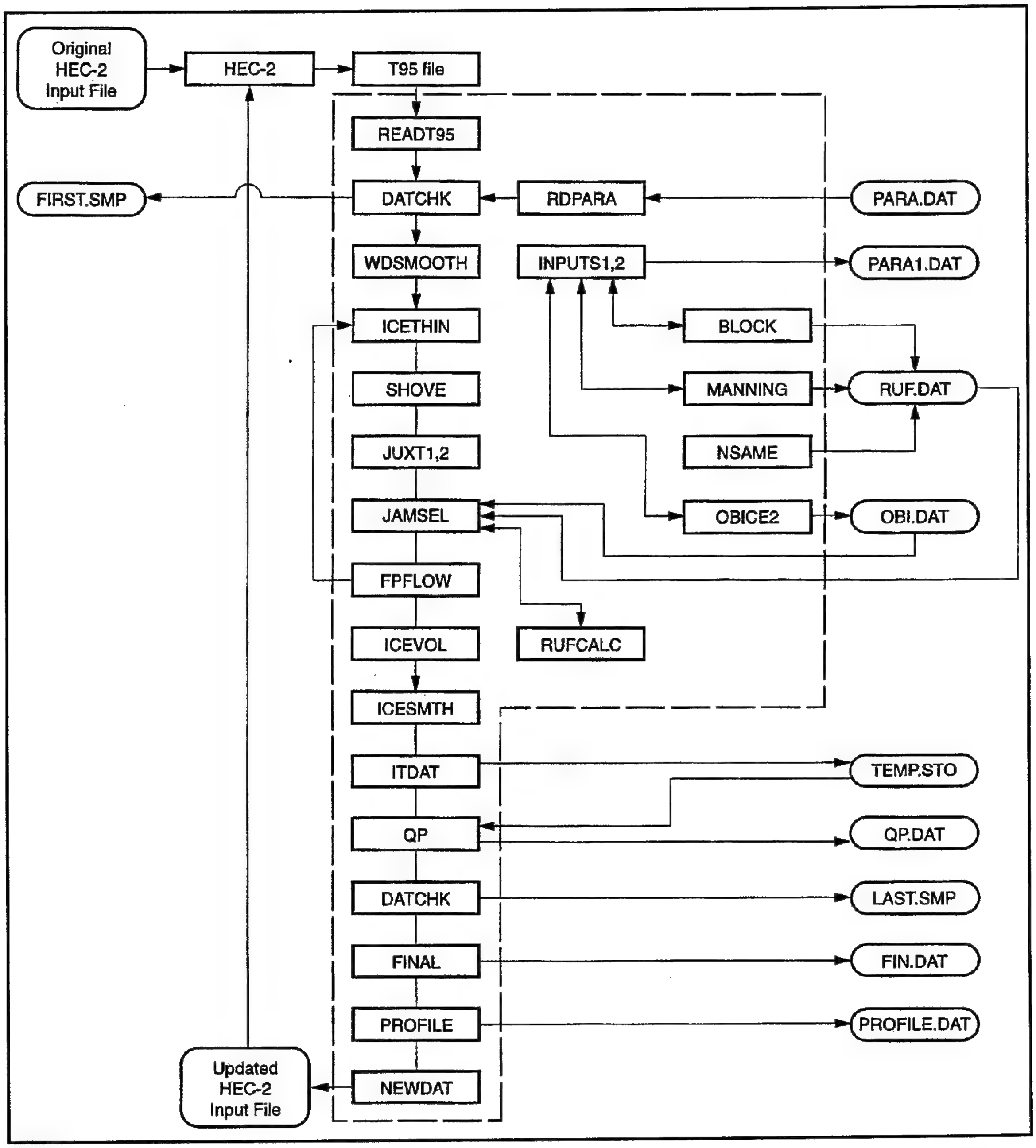

Figure 4-3. Structure of the ICETHK model. *Square-cornered boxes indicate programs and subprograms. ICETHK subprograms lie within the large dashed line box. External files (both input and output) are indicated by round-cornered boxes*

section. Different ice cover thicknesses and roughnesses can be specified for the main channel and for each overbank and both can vary along the channel. The second level is a wide-river ice jam. In this case, the ice jam thickness is determined at each section by balancing the forces on it. The ice jam can be confined to the main channel or can include both the main channel and the overbanks. The material properties of the wide-river jam can be selected by the user and can vary from cross section to cross section. The user can specify the hydraulic roughness of the ice jam or HEC-RAS will estimate the hydraulic roughness on the basis of empirical data. Published documentation (U.S. Army 1998a, 1998b, 1998c) should be consulted for a fuller discussion of HEC-RAS.

4-13. Ice Covers with Known Geometry

Separate ice thicknesses and roughnesses can be used in HEC-RAS for the main channel and each overbank, providing the ability to have three separate ice thicknesses and ice roughnesses at each cross section. The ice thickness in the main channel and each overbank can also be set to zero. The ice cover geometry can change from section to section along the channel. The suggested range of *n* values for river ice covers is listed in Table 4-1.

Table 4-1
The Suggested Range of Manning's *n* Values for a Single Layer of Ice and for Ice Jams

Single Ice Layer

Type of Ice	*Condition*	*Manning* n *Value*
Sheet ice	Smooth	0.008 to 0.012
	Rippled ice	0.01 to 0.03
	Fragmented single layer	0.015 to 0.025
Frazil ice	New, 0.3-0.9 m (1–3 ft) thick	0.01 to 0.03
	0.9–1.5 m (3–5 ft) thick	0.03 to 0.06
	Aged	0.01 to 0.02

Ice Jams

Thickness m (ft)	*Manning's* n *Value*		
	Loose Frazil	*Frozen Frazil*	*Sheet Ice*
0.1 (0.3)	--	--	0.015
0.3 (1.0)	0.01	0.013	0.04
0.5 (1.7)	0.01	0.02	0.05
0.7 (2.3)	0.02	0.03	0.06
1.0 (3.3)	0.03	0.04	0.08
1.5 (5.0)	0.03	0.06	0.09
2.0 (6.5)	0.04	0.07	0.09
3.0 (10.0)	0.05	0.08	0.10
5.0 (16.5)	0.06	0.09	--

4-14. Ice Jam Thickness Calculation

HEC-RAS estimates the ice jam thickness using Equation 4-9 above. No assumptions are made with respect to there being an equilibrium reach or not. As a result, the entire equation is solved, including the differential term with respect to *x*, the longitudinal length along the channel.

a. Force balance. To evaluate the force balance equation, the under-ice shear stress must be estimated. The under-ice shear stress is

$$\tau_i = \rho g R_{ic} S_f \tag{4-14}$$

where

R_{ic} = hydraulic radius associated with the ice cover

S_f = friction slope of the flow.

b. Hydraulic radius. The value of R_{ic} can be estimated as

$$R_{ic} = \left(\frac{n_i}{n_c} \right)^{3/2} R_i \tag{4-15}$$

c. Roughness. The hydraulic roughness of an ice jam can be estimated using the empirical relationships derived from the data of Nezhikovskiy (1964). These are the relationships described in paragraph 4-5. Note that only the relationships for breakup ice covers are available.

4-15. Solution Procedure

The ice jam force balance equation is solved using an approach analogous to the standard step method. In this, the ice thickness at each cross section is found, starting from a known ice thickness at the upstream end of the ice jam. The ice thickness at the next downstream section is assumed and the value of *F* found. The ice jam thickness at this downstream cross section, t_{ds} , is then computed as

$$t_{ds} = t_{us} + F\,L \tag{4-16}$$

where

t_{us} = thickness at the upstream section

L = distance between sections

$F = (F_{us} + F_{ds})/2.$

The assumed value and computed value of t_{ds} are then compared. The new assumed value of the downstream ice jam thickness is set equal to the old assumed value plus 33 percent of the difference between the

assumed and computed value. This *local relaxation* is necessary to ensure that the ice jam calculations converge smoothly to a fixed value at each cross section. A maximum of 25 iterations is allowed for convergence. The above steps are repeated until the values converge to within 0.03 meters (0.1 foot) or to a user-defined tolerance.

a. Tests for reasonableness. After the ice thickness is calculated at a section, the following tests are made:

- The ice thickness cannot completely block the river cross section. At least 0.30 meters (1.0 foot) must remain between the bottom of the ice and the minimum elevation in the channel available for flow.

- The water velocity beneath the ice cover must be less than 1.5 m/s (5 ft/s) or a user-defined maximum velocity. If the flow velocity beneath the ice jam at a section is greater than this, the ice thickness is reduced to produce a flow velocity of approximately 1.5 m/s (5 ft/s) or the user-defined maximum water velocity.

- The ice jam thickness cannot be less than the thickness supplied by the user. If the calculated ice thickness is less than this value, it is set equal to the user-supplied thickness.

b. Simultaneous solution scheme. It is necessary to solve the force-balance equation and the energy equation simultaneously for the wide-river ice jam. However, difficulties arise because the energy equation is solved using the standard step method, starting from the downstream end of the channel and proceeding upstream, while the force-balance equation is solved starting from the upstream end and proceeding downstream. The energy equation can only be solved in the upstream direction because ice covers and wide-river jams exist only under conditions of subcritical flow. To overcome this incompatibility and to solve both the energy and the ice jam force-balance equations, the following solution scheme was adopted.

(1) A first guess of the ice jam thickness is provided by the user to start this scheme. The energy equation is then solved using the standard step method starting at the downstream end. Next, the ice jam force-balance equation is solved from the upstream to the downstream end of the channel. The energy equation and ice jam force-balance equation are solved alternately until the ice jam thicknesses and water surface elevations converge to fixed values at each cross section. This is *global convergence*.

(2) Global convergence occurs when the water surface elevation at any cross section changes less than 0.02 meters (0.06 feet), or a user-supplied tolerance, and the ice jam thickness at any section changes less than 0.03 meters (0.1 foot), or a user-supplied tolerance, between successive solutions of the ice jam force-balance equation. A total of 50 iterations (or a user-defined maximum number) is allowed for convergence. Between iterations of the energy equation, the ice jam thickness at each section is allowed to vary by only 25 percent of the calculated change. This *global relaxation* is necessary to ensure that the entire water surface profile converges smoothly to a final profile.

4-16. References

a. Required publications.
None.

b. Related publications.

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Chapter 5
Ice-Affected Stage-Frequency Analysis

5-1. Introduction

The purpose of this chapter is to provide techniques for the determination of stage-frequency distributions for rivers subject to periods of ice. Such analyses can be important for projects dealing with ice-affected flooding, clearance for bridges or hydraulic structures, tailwater elevations for hydroelectric plants, water intake elevations, and shore protection design. In contrast to open-water flooding, where high water levels directly result from excessive water discharge, ice-affected flooding results from added resistance to flow and blockage of flow caused by accumulations of ice. Water discharge during ice-induced flooding is typically low relative to open-water floods. Consequently, a flood-frequency analysis based on peak annual discharges will often miss most, if not all, ice-affected events, even though the stages may be among the highest on record. Thus, ice-induced flooding must be analyzed in terms of stage frequency, which is primarily influenced by the ice regime.

5-2. Ice Effects on River Stage and Flooding

The formation of an ice cover or ice jam on a river roughly doubles the wetted perimeter of a wide channel. The added resistance to flow, along with the reduction in flow area caused by the ice, results in higher stages than a comparable open-water discharge would produce. This is particularly true for the case of ice jams, which can cause flood stages comparable to rare open-water events, despite discharge exceedance probabilities on the order of 0.5 or greater. These accumulations include freezeup jams, formed by the collection of pieces of floating ice during the periods of relatively steady flow experienced when the ice cover initially forms early in the winter season, as well as breakup jams, which form during the often highly unsteady flow conditions when the ice cover breaks up because of a significant rainfall event, snow melt, or other increase in runoff.

a. Ice jam flow profiles. Most ice jams are the result of ice moving downstream until it encounters an intact downstream ice cover, or other surface obstruction. Figure 5-1 illustrates the longitudinal profile of a typical fully developed jam. Downstream from the jam, the flow may be uniform (at least in a reach-averaged sense). At the downstream end, or toe, of the jam, the ice accumulation results in a gradually varied flow profile in the transition reach, as water depth increases toward the deeper normal-flow depth associated with the thicker, rougher ice conditions. If the ice jam is long enough, a fully developed or equilibrium-jam reach may form, in which ice and flow conditions are relatively uniform. From the upstream end, or head, of the jam, flow depths again transition toward the lower uniform-flow depth associated with the open-water conditions upstream.

b. Ice jam data. Ice-related flooding tends to be local and highly site specific. While ice jams may be relatively common at a given site, they cannot be predicted with certainty in any given year, and may be totally absent at other sites nearby, even along the same river. Without prior field observations, it is generally difficult to predict where, or even if, jams will form along a river. Thus, ice-affected frequency analysis emphasizes historical data, even though they may be scarcer and less reliable than the open-water data. The available information may range from detailed hydrographic records to observations by local residents. At a minimum, it is necessary to have some information on where, when, and with what frequency ice events happen. The types of available data will determine the form and reliability of the frequency analysis that can be conducted.

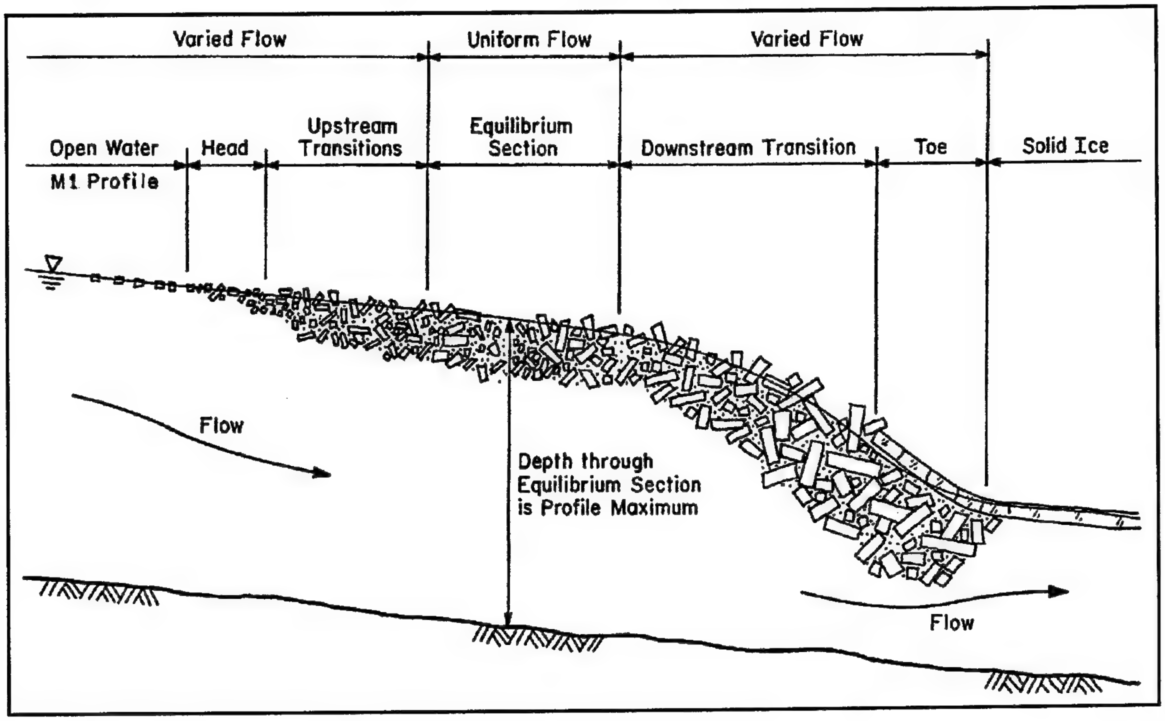

Figure 5-1. Typical ice jam profile

5-3. Data Sources

Ice jam floods often occur when flow rates are relatively low, perhaps no more than a 0.5-exceedance-probability discharge, and water levels are normally high only in the vicinity of the ice and in a backwater zone upstream. Their relatively small geographic extent (perhaps a few river miles or kilometers) and short duration (from a few hours to a few days for breakup events) make it unlikely that detailed field information will have been gathered at most sites. Even in cases where hydrographic gaging records exist for a site, the potential for gage freezeup because of cold weather, ice effects on the gage rating curve, the location of the gage relative to the ice accumulation, or direct ice action on the gage can reduce their reliability for ice events. Because ice jams are site-specific, it is generally not possible to transpose stage data from other sites along the river. Hence, it is often necessary to resort to other sources of data, sources that are often overlooked or regarded as unreliable for analysis of open-water flooding. Sources of historical data might include:

- USGS or Corps gaging station reports or files.
- Corps District or Area Office files.
- State and local water resources and Civil Defense offices.
- Prior flood insurance studies.
- Historical societies, museums, town offices, libraries.
- Newspapers, books, photographs.

- Interviews with local residents.

- Environmental indicators, such as tree scars, structural markings or damage, and vegetation trim lines.

5-4. Form of Frequency Analysis

To analyze ice-influenced flood frequency, mixed populations must be considered. Depending on the objectives of the overall project, it may be necessary to split the sample population into two or more subsets, such as open water, freezeup, solid ice cover, and breakup. Separate frequency distributions could be derived for any population subset, but in most cases a single, annual flood-frequency distribution is desired. As described by Morris (1982), this could be derived in two ways. If the annual frequency curve is derived directly from annual peak data that have not been segregated, it is called a *mixed-population frequency curve*. If the annual frequency curve is derived from two or more frequency curves developed from separate populations, it is called a *combined-population frequency curve*. The combined-population approach should be used when frequency curves derived from mixed populations exhibit sudden breaks in curvature (Morris 1982). These sudden breaks are often caused by several large events that depart from the trend of the remainder of the data and may arise from hurricane events in a normal rainfall series, rainfall events in a snowmelt dominated series, or, in the present case, ice-influenced flooding. Details on mixed-population analysis can be found in Morris (1982) and in a publication of the Interagency Advisory Committee on Water Data (U.S. Geological Survey 1982).

a. Mixed-population frequency analysis. When determining the stage-frequency distribution for a mixed population, one must first tabulate the annual peak stage for each year of record. These annual peaks are then ranked in descending order of severity, and the exceedance probability, in terms of plotting position, is determined for each event. There are several plotting-position equations that can be used, perhaps the most common of which is the Weibull equation:

$$P = m/N + 1 \tag{5-1}$$

where

P = exceedance probability corresponding to the event of rank m

m = rank of the event

N = total number of events.

(1) The Weibull equation was developed so that the exceedance probability associated with the highest ranked event would be correct, on the average. Another commonly used plotting-position equation, which is an approximation of the Beard, or median, plotting-position equation (Morris 1982), is

$$P = m - 0.3/N + 0.4. \tag{5-2}$$

The median plotting-position equation was developed so that the exceedance probability associated with the largest event would have an equal chance of being too high or too low.

(2) Once the plotting positions have been determined, the exceedance probability and stage coordinates are plotted on the appropriate probability paper. An analytical frequency curve may then be calculated

using a selected probability distribution. The Interagency Advisory Committee on Water Data (U.S. Geological Survey 1982) recommends that the log-Pearson type III distribution, with a weighted skew coefficient, be used to model annual peak discharges. However, the interagency committee's conclusions and generalized skew coefficient map were based on annual peak data that were not segregated according to causal factors. Morris (1982) suggests that, unless the annual series in a number of stations clearly contain non-zero skew coefficients, one should use the log-normal distribution. Further, it is not clear what form of distribution ice-affected stages should follow. In view of these uncertainties, it is suggested here that the log-normal distribution be used, owing to its simplicity, with all stages referenced to the zero-discharge stage. However, since ice-affected stages are primarily governed by the ice regime and its interaction with channel geometry, extrapolation beyond the range of observed data is risky. Because discharges are normally low for ice events, the frequency curve can become highly nonlinear as flow enters the floodplain. Further, as discharge increases, a point will be reached where no stationary ice accumulation is possible and a discontinuous distribution of stages can occur as the dominant factor governing stage reverts from ice processes to water discharge. As such, it is normally sufficient to graphically fit a curve through data plotted on log-normal paper. The upper limits on ice-affected stages are discussed later.

b. Combined-population frequency analysis. For a combined-population frequency analysis, the annual peaks for each subpopulation must be tabulated similarly to the way described above for the mixed-population case.

(1) The first step is to identify the significant causal factors and determine a method for separating events into subsets. One option is to separate data populations by season (such as open water, ice covered, freezeup jamming, and breakup jamming). Such seasons must be based on different hydrometeorological conditions and not be arbitrary periods, such as calendar months. However, if the data are separated into too many subsets, one or more of the subsets may contain a few large events and many small ones (Morris 1982). This causes the frequency curves of these subsets to be unreasonably steep, and a combined annual curve will predict unreasonably high magnitudes for extreme events.

(2) The procedure for combining multiple frequency curves developed from independent annual series can be expressed in general form as

$$P_c = 1 - (1 - P_1)(1 - P_2) \ldots (1 - P_n) \tag{5-3}$$

$$= 1 - \pi^{n}{}_{i=1}(1 - P_i) \tag{5-4}$$

where

P_c = exceedance probability of the combined-population frequency curve for the selected discharge

$P_1, P_2, \ldots P_n$ = exceedance probabilities associated with selected discharge from curve numbers 1, 2, through n

n = number of frequency curves to be combined.

If only two curves are combined, this reduces to

$$P_c = P_1 + P_2 - (P_1)(P_2) \tag{5-5}$$

These equations assume that each of the frequency curves used to develop a combined curve is independent, a valid assumption when combining open-water and ice-influenced events.

5-5. Approaches for Developing Ranked Data Tabulations

The discussion above has assumed that annual peak data were available for each population to be analyzed. In this paragraph, we consider how the ranked data tabulations can be developed, given the variability in data quantity and quality mentioned previously. There are two general approaches. The first is a direct analysis of historical data. The second is an indirect analysis based on data synthesized from estimates of discharge and an understanding of ice jam mechanics. The latter method is significantly more difficult than it is for the case of open-water flooding, but at the same time is typically more necessary because of the likelihood that few or no historical ice-affected data will be available. Further, it is the only feasible approach if the ice regime has changed or will be changed as a result of project construction that makes historical data obsolete. Frequently, the best approach is to use a combination of the direct and indirect methodologies.

a. Direct approach. If reliable hydrometric data are available at the site, and the desired product is a combined-frequency analysis of the open-water and ice-covered flows, the analysis is relatively straightforward. The maximum open-water and ice-covered stages should be tabulated for each water year. The two event types are independent because they have different causes (water quantity versus ice processes) and are not mutually exclusive (an open-water flood can occur in the same year as an ice-affected flood). Each of these populations can then be analyzed using standard techniques, as discussed earlier. If the desired subpopulation is ice jam events, however, a variation in technique is required, since ice jams do not typically form every year at a given site.

(1) Morris (1982) discusses several options for the somewhat comparable case of analyzing hurricane events. One applicable approach is to redefine the number of events in the plotting-position formula as being equal to the total number of years of record analyzed. This tacitly assumes that the record is continuous and that all events in the subpopulation have been identified. Morris also suggests that the frequency curve be developed by drawing a best-fit line by eye, rather than using regression equations, so that outliers do not unduly affect the derived line. Because of the small sample size typical of this type of analysis, there can be significant uncertainty in the accuracy of the resultant frequency curve.

(2) Very often, there is no long-term, reliable gaging station at the project site, and it becomes necessary to combine information from several sources of varying accuracy and reliability. There may also be years in which no data were recorded, but it is not clear whether there was no event or whether it simply was not recorded. This inhomogeneity of data can reduce the reliability of the resulting frequency curve. If the record is clearly incomplete, consideration should be given to employing the indirect method of analysis, with checks against the available historical data, as discussed later.

(3) When analyzing a data set with multiple data sources, it is necessary to determine which one is the most reliable, when more than one data source records an event, and also to determine the maximum stage that may have occurred in years when there were no reports on ice-affected stages. While there is no standard technique for this integration of data sources, a reasonable methodology has been given by Gerard and Karpuk (1979), as outlined briefly below.

(a) *Perception stage.* One must determine the minimum stage (or *perception stage*) that would be recorded by various data sources. This perception stage is defined as the minimum stage required for a

given source to perceive and record an event. For example, for a gaging station, the perception stage would be the minimum stage it was capable of recording, while for a local resident, it would be that stage below which the event would have gone unnoticed or unremembered. Newspaper accounts would require an event of interest to its readers, and photographs would require an event significant enough for a person to want a permanent record (unless the event was captured incidental to a different subject). The significance of the perception stage is that, if a source was in a position to observe events during a given year, but didn't report any, then one can presume that the maximum stage during that year was less than the perception stage of the source. This simple constraint provides an objective means of merging data from several sources and of increasing the record length beyond the recorded number of events.

(b) *Environmental indicators of stage.* Environmental indicators, such as structural markings and high-water marks, can be used, providing one knows when they happened. The same is typically true for other environmental evidence, except that it is sometimes possible to date old tree scar data by analyzing tree rings. This has been used with success in prior studies to document high-water levels that were several decades old. In either case, analysis can be complex, since a stable object would have to have been located at a proper location and elevation to allow recording, and the markings would have had to be high enough and long lasting enough to persist through subsequent floods.

(c) *Record length.* In this method, the record length will vary with stage. Record length for an individual peak is equal to the number of years in which any source with a perception stage lower than that peak was present on the river. For example, assume that the hypothetical data in Table 5-1 came from three different sources, such as 1) the memory of a local resident, 2) an early water-level gage, and 3) a more recent water-level gage. Perception stages of 2.7, 0.9, and 0 meters (9, 3, and 0 feet), relative to a zero-flow stage, have been assigned to these sources. Further, assume that the local resident was present throughout the period of record, but that the first water-level gage operated only in years 7–14 and the final gage operated in years 15–20, except when it malfunctioned during year 19. Under this scenario, if the third source recorded a stage of 0.88 meters (2.89 feet), the record length associated with that event would correspond to only the 5 years for which that source reported data. If the first data source had reported a stage of 3.05 meters (10 feet) during the first 6 years, the record length for that event would equal the total number of years that any of the three sources were active, since any of the three sources would have recorded the event had they been present.

(d) *Stage ranking.* This method also requires a modified technique for determining the rank of peak stages. When the data are tabulated for such a scenario, the rank for an individual peak is determined by ranking all peaks having a perception stage less than or equal to the value of the peak. Thus, peaks above 2.7 meters (9 feet) would be ranked in terms of the entire data set, but peaks between 0.9 and 2.7 meters (3 and 9 feet) would only be ranked with those events from the second and third sources, since an event of that magnitude may have occurred during the years when only the first source was active and gone unnoticed. As noted in Table 5-2, this can result in two or more peaks being assigned equal rank, but their record length will differ.

(4) Plotting positions can now be calculated using standard formulations and the redefined values of record lengths and rank, and the stage-frequency distribution determined as before. Although this method allows a logical means of combining inhomogeneous data sets, the discontinuities in record lengths and rank can persist as discontinuities in plotting positions. Although there are a number of available plotting-position formulas (the Weibull simulation was used in Table 5-2), they all basically divide rank by record length without any other reference to the associated stage. Thus, it is possible for an event of record length 20 and rank 7 to have the same calculated plotting position as an event of record length 14 and rank 5. For example, if the missing record from year 19 had an actual stage of less

Table 5-1
Example Historic Data Set

Year	Data Source*	Perception Stage m	Perception Stage ft	Stage m	Stage ft	Record Length
1	1	2.7	9	3.20	10.5	20
2	1	2.7	9	—	—	—
3	1	2.7	9	—	—	—
4	1	2.7	9	—	—	—
5	1	2.7	9	3.66	12.0	20
6	1	2.7	9	3.05	10.0	20
7	1,2	0.9	3	—	—	—
8	1,2	0.9	3	4.59	15.05	20
9	1,2	0.9	3	0.96	3.15	13
10	1,2	0.9	3	1.18	3.88	13
11	1,2	0.9	3	1.00	3.28	13
12	1,2	0.9	3	1.19	3.89	13
13	1,2	0.9	3	—	—	—
14	1,2	0.9	3	2.88	9.46	20
15	1,3	0.0	0	6.58	21.59	20
16	1,3	0.0	0	2.48	8.15	13
17	1,3	0.0	0	0.88	2.89	5
18	1,3	0.0	0	5.22	17.12	20
19	1	2.7	9	—	—	—
20	1,3	0.0	0	1.97	6.45	13

* Key:
1. Memory of a local resident
2. Early water-level gage
3. Recent water-level gage

than 2.48 meters (8.15 feet), then the record length for the event in year 16 would have been 14 and the plotting position would have been 0.333, equal to that for the event in year 14. By similar reasoning, it is possible to calculate a given stage as being more probable than a lesser stage, which is clearly not realistic. If such an overlap of data groups occurs, it is generally slight, and is best treated as data scatter with the final frequency-distribution curve smoothed by eye.

b. Indirect method. The indirect method of stage-frequency analysis uses stage data synthesized from estimates of discharge frequency and knowledge of ice processes. While data synthesis is more difficult than in the open-water case, it is also more necessary because of the general lack of appropriately sited gaging stations or other sources of historical data. Further, it is the only feasible approach if the ice regime has changed or will be changed, making historical data obsolete. Major obstacles to be overcome include estimating the appropriate ice conditions and assessing the frequency of ice jamming at a particular site.

Table 5-2
Example Data Tabulation

Year	Stage, m (ft)	Perception Stage, m (ft)	Record Length	Rank	Plotting Position
15	6.58 (21.59)	0.0 (0)	20	1	0.048
18	5.22 (17.12)	0.0 (0)	20	2	0.095
8	4.59 (15.05)	0.9 (3)	20	3	0.143
5	3.66 (12.0)	2.7 (9)	20	4	0.190
1	3.20 (10.5)	2.7 (9)	20	5	0.238
6	3.05 (10.0)	2.7 (9)	20	6	0.286
14	2.88 (9.46)	0.9 (3)	20	7	0.333
16	2.48 (8.15)	0.0 (0)	13	5	0.357
20	1.97 (6.45)	0.0 (0)	13	6	0.429
12	1.19 (3.89)	0.9 (3)	13	7	0.500
10	1.18 (3.88)	0.9 (3)	13	8	0.571
11	1.00 (3.28)	0.9 (3)	13	9	0.643
9	0.96 (3.15)	0.9 (3)	13	10	0.714
17	0.88 (2.89)	0.0 (0)	5	5	0.833

(1) As in the open-water case, discharge and meteorological data may be used to generate probable ice-related events for each year of record. The period stage-frequency distribution is then developed using the appropriate ice-cover-period or ice-jam-period discharge frequency, available ice data, an analysis of probable ice-related water levels (i.e., HEC-RAS, see Chapter 4), and some estimate of jam frequency.

(2) The first step is a year-by-year analysis of flow records to determine the maximum annual discharge for each desired subpopulation. Ideally, these values would reflect the instantaneous peak flows, since they are the ones that determine the severity of ice effects. On the other hand, a careful review of the records is required to ensure that the flows are from the ice-jam period, and not an open-water peak following the final breakup ice run. If necessary, these data may be transposed from gage data elsewhere on the river, transposed from other rivers in the vicinity, or estimated using a precipitation-runoff model. Next, representative ice conditions must be estimated for the range of expected breakup events. Such information might include estimates of ice thickness, ice-cover or ice-jam roughness, position of the ice jam's toe and head, and the upstream length of river contributing ice to a jam.

(3) Lacking field data, it is very difficult to predict where, and with what frequency, jams will form along a river, and analysis is often limited to estimating upper and lower limits of probable stages. If a jam is known (or assumed) to form at a given location, it is possible to estimate the maximum resulting flood levels. It can be shown that, for a given scenario of water discharge and ice conditions, the maximum water levels will occur within the equilibrium portion of the jam described earlier. Since ice and flow conditions are relatively uniform within the equilibrium reach, it is a fairly simple matter to estimate the water levels in this portion of the jam. Depending on where a jam forms, and whether there is a sufficient upstream ice discharge to form a jam long enough to develop an equilibrium reach, actual water levels may be less and the estimate will be conservative.

(4) Thus, if no site information is available, the range of possible ice conditions might be assumed to include the limiting conditions of a solid cover of sheet ice and a fully developed equilibrium ice jam. The solid-ice-cover case would represent the minimum ice-affected stage, while the equilibrium-ice-jam case would represent the maximum stage possible for a given discharge. If, for example, we were to assume that the problem at hand is an analysis of flooding attributable to breakup jams in the spring, and that little or no information exists for the ice regime, a suggested procedure is as follows.

(a) *List peak flows.* Develop a table of peak flows for the period of breakup, as discussed above. These flows should be estimates of the instantaneous peak flows, since they are the ones that govern the maximum severity of the event.

(b) *Define range of flows.* From this tabulation of flows, select a range of flows from discharges too low to cause breakup of the ice cover to discharges where all ice would move downstream without jamming. These estimates might be based on personal observations, observations by local residents, notes on nearby gaging records, sharp breaks in the trend of continuous stage measurements, or other sources of information. These estimates might also vary through the winter because of variations in ice strength. If such estimates are not possible, select a range of flows representative of all historical breakup period flows.

(c) *Calculate stages.* For a number of discharges covering the range of flows defined in the preceding paragraph, calculate the stages associated with both the solid-ice-cover and equilibrium-ice-jam cases using either a numerical model such as HEC-RAS or manually using a procedure such as the one outlined in Beltaos (1983).

(d) *Develop rating curve.* Using the above information, develop a stage-discharge rating curve for both the lower bound of a solid ice cover and the upper bound of an equilibrium ice jam.

(e) *Rank stages.* From the tabulation of historical discharges and the stage-discharge rating curve, develop a ranked tabulation of estimated historical stage data. As in the direct method, a stage-probability distribution may now be developed for the upper and lower bound cases by assigning plotting positions and plotting on log-normal paper.

(5) The task of developing a compromise distribution from these upper and lower bound distributions remains, and one should consider limiting conditions on the stage-discharge relations. The first limit is the discharge (or stage) at which the ice cover is expected to break up, as described above in paragraph 5-5*b*(4)(b). If this lower limit can be estimated, then it can be assumed that the solid-ice-cover curve is appropriate for all discharges below that level.

(6) If a large floodplain exists at the site, it may provide an upper limit on ice-induced stages. Since ice-related discharges are typically low relative to open-water events, once the stage is high enough to allow water to enter the floodplain, the slope of the stage-discharge curve should flatten considerably. Further, with continued increases in discharge, a point may be reached at which no stable ice jam is possible—all ice will simply be transported downstream. The development of an ice jam can also be limited by the volume of ice available for accumulation. If there is some physical limit to the upstream river length contributing ice (e.g., the presence of an upstream dam), there may be an insufficient ice supply to develop an equilibrium jam at the project site. Thus, extrapolation of ice-induced stages to more extreme events is generally not reliable, particularly if such limiting factors are not considered.

(7) Beyond imposing such limits, developing a compromise distribution between the ice-cover and ice-jam distributions is largely a matter of engineering judgment. If the results are to be used for project design, it might be desirable to conservatively assume that ice jams always form and employ that distribution. However, for the determination of average annual damages, even a few reliable historical data could be of immense help in the interpretation of the two analytically derived distributions. By comparing a historical observation with the analytical estimates for a comparable event (and using judgment), a compromise best-estimate of the stage for an event of that magnitude can be developed.

(8) If no such data are available, some idea of the frequency of significant ice jamming in the vicinity of the site can be helpful (e.g., do jams occur every other year, or in about 3 out of 10 years?). Although not related to specific years, this general information can be used in the development of a compromise curve (Figure 5-2) by employing the methodology of Gerard and Calkins (1984) as follows:

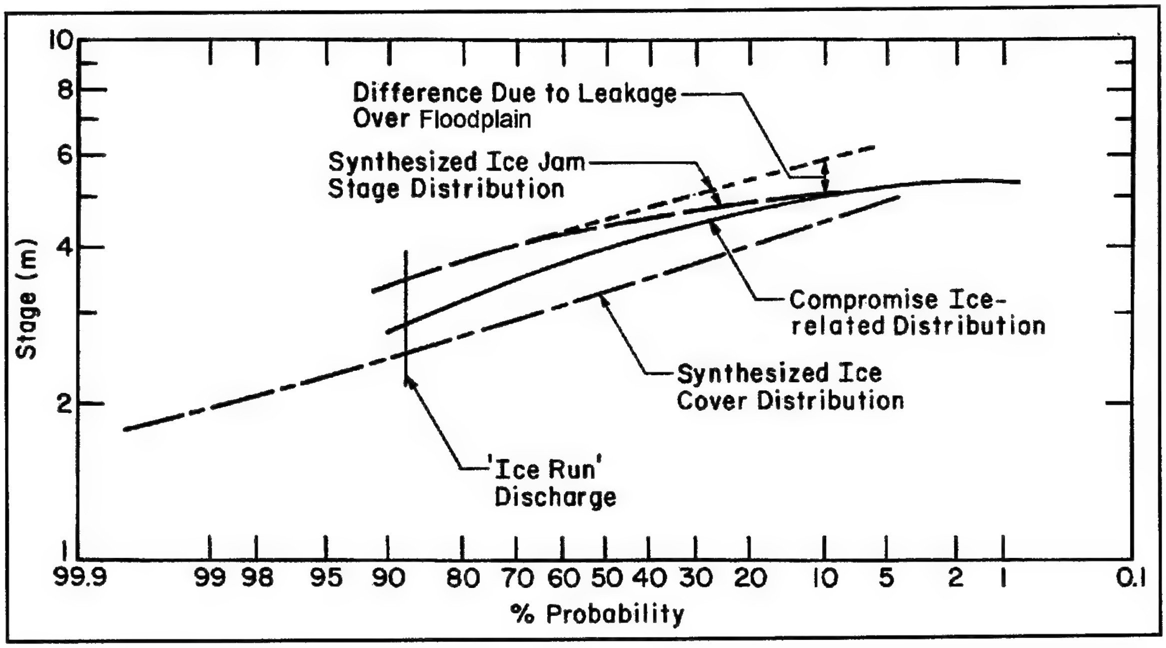

Figure 5-2. Development of a compromise distribution

(a) *Probability of stage exceedance because of jamming.* If the probability that a significant ice jam may form in a given year is $P(J) = m/N$ (m being the estimated number of jam events in N years), then the probability $P(\$_J)$ of a given stage being equaled or exceeded in a given year is given by

$$P(\$_J) = P(J) \cdot P(\$ / J) \tag{5-6}$$

where $P(\$ / J)$ is the probability of the stage being exceeded if an ice jam forms (i.e., a conditional probability). $P(\$ / J)$ corresponds to the probability coordinate of the upper bound for a given stage.

(b) *Probability of stage exceedance because of a solid ice cover.* The probability $P(\$_C)$ of the stage being exceeded when a solid ice cover exists is likewise given by

$$P(\$_C) = P(C) \cdot P(\$ \mid C) \tag{5-7}$$

where $P(C) = 1 - P(J)$ is the probability of a significant ice jam not occurring (and therefore the peak stage being associated with a solid ice cover), and $P(\$ \mid C)$ is the conditional probability of the stage being exceeded if a significant ice jam does not form (the lower bound).

(c) *Probability of stage exceedance because of ice in general.* As the ice cover and ice jam situations are mutually exclusive, the probability $P(\$)$ of a stage being equaled or exceeded is given by

$$P(\$) = P(\$_J) + P(\$_C). \tag{5-8}$$

Thus, if a jam forms in about 3 out of every 10 years, $P(J) = 0.3$ and

$$P(C) = 1 - P(J) = 1 - 0.3 = 0.7.$$

For a given stage, $P(\$ \mid J)$ and $P(\$ \mid C)$ are determined from the upper and lower bound frequency curves, respectively. Equation 5-8 can then be used to calculate the compromise probability $P(\$)$ of a given stage being exceeded.

(9) Repeating this procedure for the range of breakup flows allows the development of a compromise frequency curve between the upper and lower bounds. However, at the lower end it should merge with the solid-ice-cover case at a point where the discharge would be too low to cause ice-cover breakup, and the upper end must be reconciled with the limits imposed by floodplain flow or a finite ice supply as discussed earlier. It must be emphasized that extrapolation of ice-induced stages to extreme events is generally not reliable, particularly if such limiting factors have not been considered.

5-6. Summary

This chapter has reviewed methodologies for the analysis of ice-related flood frequency. Since ice-induced flooding is dominated by ice processes, rather than water quantity, we have emphasized the need for a stage-related, rather than discharge-related, analysis. Further, since detailed data for ice-affected events are typically unavailable, and the site-specific nature of ice-related flooding generally precludes transposing data from other sites, methodologies are outlined for performing the analysis based on limited historical data and data synthesized from discharge records and estimates of ice conditions.

5-7. References

a. Required publications.
None.

b. Related publications.

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Chapter 6
Ice Forces on Structures

6-1. Introduction

Basically, three approaches may be taken to determining ice forces on structures:

- Analytical, using the mechanical properties of ice and theory of applied mechanics.
- Experimental, using measurements from full-scale structures or scale models.
- Empirical, using the experience of successful and unsuccessful structures.

There are at present many difficulties with a strictly analytical approach, and current practice tends to depend more on empirical procedures, modified to some degree by experimental and analytical results. The concept of a design ice pressure—normally regarded as total ice force, divided by projected area of contact, normal to the direction of ice action—is firmly entrenched in engineering practice and is generally useful, being analogous to concepts of wind pressure or soil pressure. It must be emphasized, however, that ice pressure is not the same as ice strength, and that the relationship between pressure and strength depends on the geometrical relationship and other details of ice–structure interaction. The ice strength should be defined in relation to a particular test procedure and should be regarded as a material property.

6-2. Main Types of Ice–Structure Interaction

Most cases of ice action on structures fall into one of the four following categories. This chapter covers the first two types of forces only. Research on the second two types is still being conducted and the reader should contact appropriate research organizations.

a. Dynamic ice forces. These forces come from floating ice sheets and floes driven by streamflow, currents, or wind. This is normally the critical mode of action for structures in rivers and may be so in some lake situations. If the structure face subject to ice impact is vertical, the ice normally fails by crushing and splitting, and the forces that develop are horizontal. If the structure face is sufficiently inclined, the ice fails by bending and shear, and both horizontal and vertical force components are developed.

b. Static ice forces. These forces come from a more or less intact ice sheet subject to thermal expansion and contraction, or subject to steady pressure from wind or currents. Normally, the ice does not fail, but deforms plastically around the structure.

c. Ice forces from a mass of broken pack or "rubble" ice driven against a structure. This happens in a river ice jam or along lake shores. The ice pack acts somewhat like a granular soil. Pile-up on shore and forces on ice booms, bridges, and other structures fall into this category.

d. Uplift and drawdown forces. These forces are associated with adhesion of floating ice to piles, etc. Forces are generated when static water pressures change because of tides, reservoir operation, lake level changes, etc.

6-3. Dynamic Forces—General

Most ice sheets are large enough so that impact forces are limited by ice failure in the weakest mode permitted by the mechanics of the interaction as the structure penetrates the ice—crushing, splitting, shear, or bending. For smaller sheets or wide structures, the maximum force may be limited by the kinetic energy available at the moment of impact and complete penetration may not occur.

a. *Vertical surfaces.* With vertical piles, pier noses, etc., failure usually takes place by crushing at the surface of contact (Figure 6-1). Spalling may occur on top and bottom ice surfaces, and thin sheets may buckle. A neat slot is often left as the ice moves past. (If the ice sheet is large enough, current drag can maintain a steady speed.) Smaller sheets may crush briefly and then stop, rotate and move downstream, or they may split longitudinally.

b. Inclined surfaces. The mode of ice failure for inclined faces is variable and complex (Figure 6-2). At angles of greater than 75 degrees between the pier nose and the horizontal, crushing failure is most likely. At intermediate angles of inclination, some ice may crush, while other ice "rides up" and breaks in a three-dimensional pattern. If the inclination angle is less than 60 degrees, failure is nearly always by shear–bending. Factors such as friction, pier-width-to-ice-thickness ratio, and cracks in the sheet affect the preference for crushing or bending failure. Horizontal forces from bending failure are far less than forces from crushing failure; therefore, inclined faces are desirable. However, other considerations (economics, catching of driftwood, etc.) have led to a decline in the popularity of severely inclined faces for river piers.

c. Conical structures. Conical towers are favored for coastal and ocean structures (e.g., lighthouses), since ice fails by bending into wedge-shaped slabs (Figure 6-3).

d. Force fluctuations. A more or less universal characteristic of dynamic ice forces is the presence of rapid force fluctuations, which may be periodic or random, or both. Their significance depends on the dynamic response characteristics of the structure. No special allowance for forced vibrations has normally been made in pier design. In the case of sloping structures, a lower-frequency periodic fluctuation results from a ride-up and break sequence.

6-4. Vertical Piers or Piles

Currently, all bridges are designed using AASHTO specifications. A standard of 2.76 MPa (400 psi) is used as the crushing strength of the ice, and the design load is obtained by multiplying this times the ice thickness and times the pier width

$$\frac{P}{bh} = 2.76 \text{ MPa (400 psi)}. \tag{6-1}$$

Analysis and experiments indicate the existence of something like the following basic relationship

$$\frac{P}{bh} = C_i \cdot m \cdot \sigma_c \cdot k \tag{6-2}$$

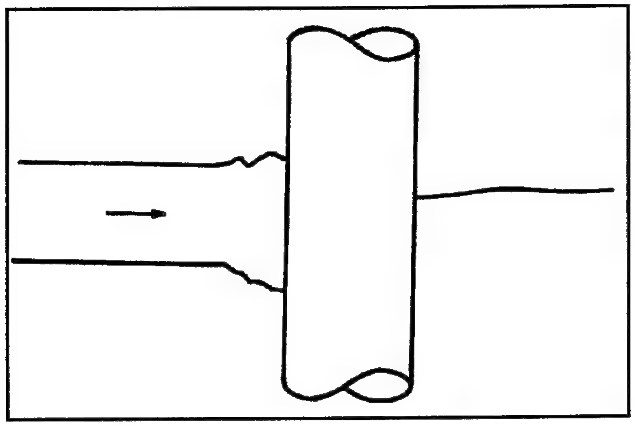

Figure 6-1. Ice failing against a vertical surface

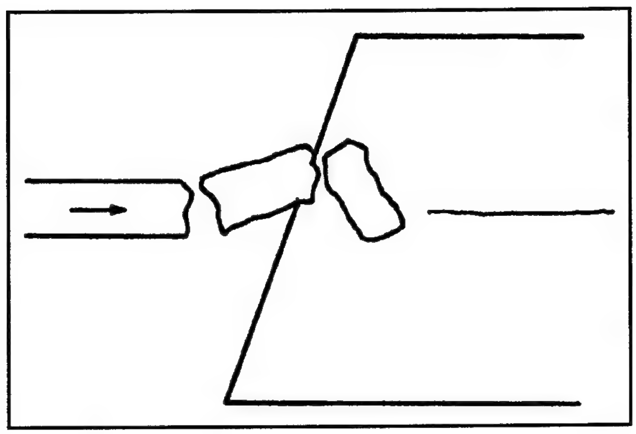

Figure 6-2. Ice failing against an inclined surface

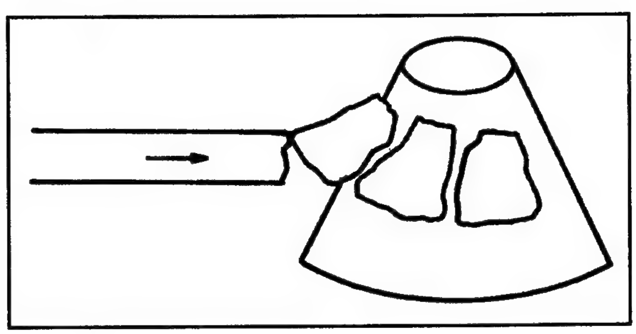

Figure 6-3. Ice failing against a conical surface

where

P = horizontal force developed

C_i = "indentation" coefficient

m = plan shape coefficient

σ_c = compressive strength of ice

b = width or diameter of pile or pier normal to ice movement

h = ice thickness

k = "contact" coefficient.

The ice pressure P/bh is therefore equal to the ice crushing strength σ_c multiplied by three coefficients. The indentation coefficient C_i is found experimentally and analytically to be a function of b/h, as given by Figure 6-4. The shape coefficient m is not very sensitive to plan shape and is usually taken as 0.9 for semicircular noses. Korzhavin (1971) quoted the "contact" coefficient as in the range of 0.4 to 0.7. The combination $m \cdot k$ is therefore on the order of 0.5.

a. Effective ice strength. The current Canadian bridge design code provides for "effective ice strength" values ranging from 0.69 to 2.76 MPa (100 to 400 psi), and for modifying factors, dependent on b/h, that follow the curve shape of Figure 6-1 but imply an included $m \cdot k$ value of about 0.5. The background to these code values is difficult to explain in a few words since it has undergone successive modifications. However, the Canadian code does recommend an "effective ice strength" of

0.69 MPa (100 psi) when breakup occurs at melting temperatures and the ice moves in small pieces that are essentially disintegrated.

1.38 MPa (200 psi) when breakup occurs at melting temperatures but the ice moves in large pieces that are generally sound.

2.07 MPa (300 psi) when breakup consists of an initial movement of the entire ice sheet or when large sheets of sound ice strike piers.

2.76 MPa (400 psi) when breakup occurs with an ice temperature significantly below the melting point and the ice movement consists of large sheets.

The AASHTO 1978 interim specifications have essentially adopted the Canadian code.

b. Other considerations. If values of ice compressive strength are determined for a specific situation, insertion into Equation 6-2 of values of C_i taken from Figure 6-4 will probably give reasonable values of P when $m \cdot k$ is taken as about 0.5. Note that because of the dependence of C_i on b/h, ice force does not reduce in proportion to pier width, especially at low values of b/h. In the limit, a knife-edge pier will still experience substantial forces.

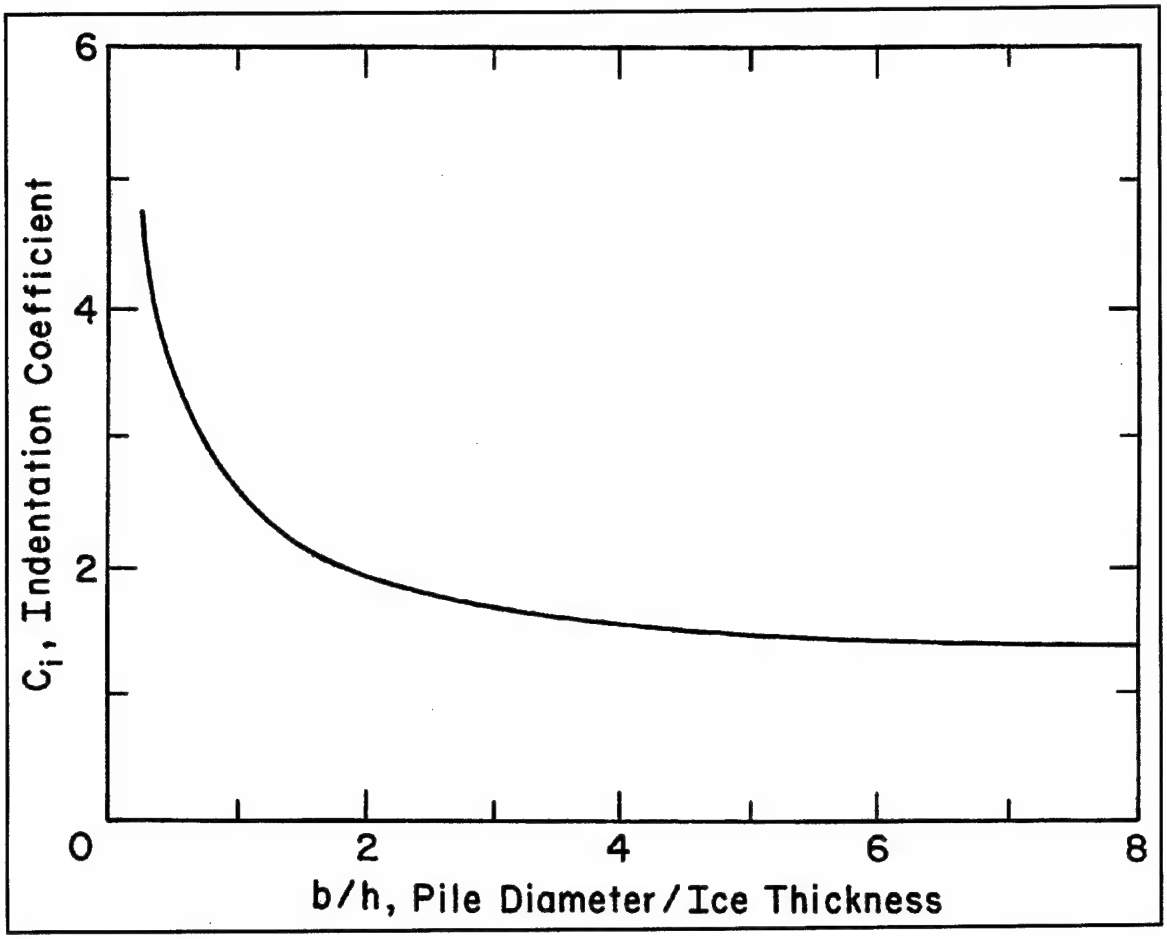

Figure 6-4. Indentation coefficient versus *b/h*

6-5. Dynamic Forces—Inclined Piers

The problem of calculating the forces on inclined piers has been attacked analytically many times since the 19th century, with considerably varying results, depending upon the assumptions made. Because of these variable results, the approach has usually been to consider static forces rather than dynamic forces that vary with time. Some formulas make the force proportional to bh, and others to h^2. Experimental evidence is insufficient to settle the question, but intuition suggests that the truth lies somewhere between these extremes. On the basis of dimensional analysis, it appears to be immaterial which is used, because the ratio of force to bh or to h^2 should depend in part on the aspect ratio b/h, as in the vertical case.

a. Reduction coefficient. The current Canadian code takes a conservative approach to inclined piers by providing reduction coefficients to the basic formula of Equation 6-2. If the angle of the pier nose to the horizontal is less than 75 degrees, a reduction factor of 0.75 is used, and if the angle is less than 60 degrees, 0.50 is used.

b. Example. Consider an ice sheet 3 feet (0.9 meters) thick failing against a 5-foot-wide (1.5-meter-wide) pier that slopes 65 degrees with respect to the horizontal. Assume the compressive strength of the ice to be 400 psi (2.76 MPa). Equation 6-1 gives

$P = (0.75)\ (400\ \text{psi})\ (36\ \text{in.})\ (60\ \text{in.}) = 648{,}000\ \text{lb.}$

In SI units

$P = (0.75)\ (2.76\ \text{MPa})\ (0.9\ \text{m})\ (1.5\ \text{m}) = 2.79\ \text{MN.}$

6-6. Dynamic Forces—Conical Towers

In the case of conical towers, the ice failure pattern is complex and the force on the pier apparently depends substantially on the resistance of the broken ice to displacement, as well as on breaking forces. Generally speaking, the horizontal force depends primarily on the ice thickness, the strength in bending, and the cone angle, but also on the waterline diameter and the coefficient of friction between ice and cone. For steep angles, results are sensitive to assumed friction and the crushing mode of failure may occur. Since very few conical structures have been built, the state of the art is constantly changing and consultation with a research organization such as CRREL is recommended for particular problems.

6-7. Transverse Forces on Piers

The 1978 Canadian code provides that the transverse force shall be not less than 15 percent of calculated axial force, or the appropriate component based on angle of approach, if known. This provision implies penetration of the ice by the pier nose and is not intended to provide for sideways impact on a vertical face, which might produce very large forces.

6-8. Static Force—Thermal Expansion

Equations are available that predict the temperature of ice based on an energy balance between the atmosphere and the ice. The atmospheric parameters needed are air temperature, air vapor pressure, wind, and cloud cover. The thermal expansion of unrestrained ice behaves as most normal materials do. The thermal strain is equal to a thermal expansion coefficient times the change in temperature. If the ice is restrained or partially restrained, the stress–strain law for ice must be used to predict the thermal stress. This law is nonlinear with stress and is time-dependent. For example, if the ice temperature changes slowly, the induced thermal stress will have time to relax owing to creep of the ice. Hence, the rate of temperature change is an important factor in predicting thermal stresses. The effect of a snow cover is to slow down the rate of temperature change. Even a thin snow cover can reduce thermal stresses drastically. Recent practice in Canada is to design for 146–219 kN/m (10,000–15,000 lb/ft) for dams and other rigid structures. For flexible structures, such as sluice gates, 73 kN/m (5000 lb/ft) is used. Values measured by the Bureau of Reclamation on reservoirs are from 51 to 292 kN/m (3500 to 20,000 lb/ft). The higher value is for a reservoir with steep, rocky banks. Closely spaced spillway piers at a dam are designed with an increased effective pier width. The effective pier width is equal to the actual pier plus one-third of the pier spacing distance.

6-9. References

a. Required publications.
None.

b. Related publications.

Korzhavin 1971
Korzhavin, K.N. 1971. *Action of Ice on Engineering Structures*, Draft Translation, TL 260, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Chapter 7
Sediment Transport

7-1. Introduction

Ice and low temperatures play many roles in sediment transport and shoreline change. Ice formed on a shore or riverbank may isolate and thereby protect the soil. Ice formation can, however, cause significant local shoreline damage by gouging ordinarily stable beach or bank formations, removing protective vegetation, adfreezing sediment at the ice/soil interface, and entraining sediment within the ice structure. During spring breakup this nearshore ice may migrate considerable distances before melting and releasing the entrapped sediment. Even if the rate at which material is removed from a river or steep coastal bluff is small, it can be significant since this material is not easily replaced in nature. Ice jams, frazil dams, or other ice irregularities that cause a constriction of flow can increase velocities and cause scour. These same features can also deflect the flow of a river against an erodible bank or bed area.

a. Ice also affects the general hydraulics of a system. In a coastal zone, for example, ice tends to damp the effects of winds, waves, and currents during severe winter storms. The influence of the development and presence of an ice foot on nearshore bathymetry is, as yet, undefined. This nearshore bathymetry is important in the dissipation of wave energy during ice-free periods.

b. A complex interaction exists among the ice cover, fluid flow, and sediment and bed forms. The presence of an ice cover roughly doubles the wetted perimeter of a wide channel, which in turn affects the magnitude and distribution of water velocities and the boundary and internal shear stresses. In addition, the lower water temperatures associated with the presence of ice affect fluid properties, such as viscosity, which in turn alter the fall velocities of sediments. As an added element of complexity, the boundary roughness is not constant, since the roughness of both the sediment bed and ice cover may vary with composition, form, and time.

7-2. Sediment Transport Under Ice

Sediment discharge in ice-covered streams has not been widely studied to date. The techniques of measuring sediment discharge for periods of ice cover are quite different from those used during open-water conditions. People and equipment have problems functioning during severe winter conditions. The relatively unknown nature of the interaction of ice with sediment transport and the variability of ice conditions that affect this interaction also present a problem. While there have been some studies to evaluate the resistance to flow for ice-covered streams, there has been little documentation of sediment transport or bed forms for ice-covered streams. Because of the uncertain accuracy of winter measurements, even the limited amount of field data available is subject to question.

a. The effects of temperature on sediment transport have received fairly extensive study but are not yet fully understood. The primary effect of temperature is to change the viscosity of the water (the kinematic viscosity of water more than doubles when the temperature drops from 80°F [27°C] to near freezing). The decrease in sediment particle fall velocity attributable to this increase in water viscosity should increase suspended sediment discharge.

b. In general it might be expected that the added resistance to flow caused by an ice cover would reduce flow velocities and thereby increase water depth. Because of the reduction in flow velocity, bed

shear stress and sediment discharge would also be reduced. However, when an ice jam or a hanging dam is present, flow may be impinged and the bed may be scoured.

c. Changes in water velocity may also affect bed shear and alluvial bed form. If the bed form is altered, the bed roughness and flow velocity may change substantially. Depending on a number of initial conditions, such as bed form, sediment characteristics, and flow regime, a decrease in water temperature could increase, decrease, or have very little effect on sediment transport. Although the effects of water temperature on sediment transport have been under study for some time, the resulting information is contradictory and confusing.

d. The effect of an ice cover on sediment transport and alluvial bed form has received almost no study. From related work on sediment transport in closed conduits, it appears that the presence of a surface boundary has a strong effect on the water velocity profile and on the distribution of pressure and shear stress.

e. The hydraulic roughness of ice covers has been studied by numerous researchers in the past, but because of the variability of ice conditions, a wide range of roughness values has resulted. Values of Manning's n have ranged from 0.008 to 0.10, corresponding to smooth sheet ice ranging up to thick ice jams. As with alluvial bed roughness, the ice roughness may vary with location on a river and with time. In addition to the shear resistance of a smooth ice cover, ripples (somewhat similar to those on an alluvial bed) may form, and there may be additional roughness from frazil deposits or other ice irregularities.

f. In summary, while it is clear that, for otherwise constant conditions, the addition of an ice cover should reduce flow velocity and sediment transport, the magnitude of this change is unknown. In addition there are the unknown influences of the ice cover on a shift in alluvial bed form and of the interaction of ice cover effects with water temperature effects. The limited amount of work on this is inconclusive and often contradictory. Further research is needed to allow accurate measurement or analysis of sediment transport, erosion, and deposition with ice present, as well as analysis of the combined influence of an ice cover, water temperature, and an alluvial riverbed on river flow depths and velocities.

7-3. Effects of Winter Navigation

Winter navigation may aggravate any natural effects of ice by disrupting the natural ice cover. Similarly, an ice cover may alter and even amplify the effects of navigation on system hydraulics and sediment transport. Specific sites have been studied to gain an understanding of the mechanics of the interaction between large-scale navigation and the hydraulics of a river system. This mechanistic approach is required, since vessel-related effects consist of short periods of intense and rapid activity between long periods of relatively mild conditions. In addition, until recently, few ships have operated through the entire winter in the areas studied.

a. In navigable waterways, there are several ways in which vessel passage can affect sediment transport and shoreline erosion, including direct movement of ice in contact with vessels, propeller wash, wave action, and other hydraulic effects. The significance of these effects depends on a number of local conditions, and the presence of other transport agents, such as natural currents or waves.

(1) Shore damage by lateral ice movement caused by vessel passage is ordinarily small, being limited to early or unstable ice conditions and shore areas close to the navigation track. The resulting damage, while possibly significant, is unpredictable, infrequent, and difficult to quantify. A long section of

shoreline may or may not be affected in any one year. As a result, structural shore protection would be difficult to apply and most likely be uneconomical. The regulation of vessel speeds in affected areas during periods with certain ice conditions may provide the best method of preventing damage.

(2) Propeller wash, while sometimes significant, is generally unaffected by the presence of ice. It is also localized and distant from the shore, and so will not be considered here.

(3) Wave action is normally associated with ship-induced shoreline erosion. When a ship is in motion, a system of diverging and transverse waves develops. Diverging waves form the familiar V-shaped wave pattern associated with ship passage, while transverse waves form a less noticeable wave train that follows a vessel and is oriented normal to the sailing line. The waves produced by large-scale navigation are generally much smaller and less damaging than those produced by recreational craft, particularly when vessel speed and distance to shore are considered.

(4) Although ship waves and other hydrodynamic effects of vessel passage have been studied in terms of vessel maneuverability and power requirements, the effects of vessel passage are not yet understood in terms of natural flow patterns and distribution, and adverse environmental effects. Information for periods of ice cover is almost nonexistent.

b. When a vessel is in motion, even in deep water, the water level in the vicinity of the ship is lowered and the ship with it (vessel squat). For the same ship, this effect increases as vessel speed increases or as water depth decreases. When a ship enters restricted water areas, there is a considerable change in flow patterns about the hull. The water passing beneath the hull must pass at a faster rate than in deep water, and as a result there is a pressure drop beneath the vessel that increases vessel squat. In a channel that is restricted laterally, this effect is further exaggerated. A vessel in a laterally restricted channel may encounter a condition that tends to push the bow away from one side of the channel and draw the stern toward it. These effects can occur independently when a channel is restricted either laterally or vertically and unrestricted in the other direction.

c. There is, however, another problem associated with the water level drop caused by the presence and movement of a ship in restricted waters. This water level drop in the vicinity of the ship is in effect a trough that extends from the ship to the shore and that moves along the river or channel at the same velocity as the ship. As the ship's speed increases, the moving trough deepens. One can understand the phenomenon of nearshore drawdown and surge during vessel passage in terms of the moving trough. In sufficiently deep water, the moving trough appears as a fluctuation in the elevation of the water surface (the transverse wave). To an observer in a shallow or nearshore area where the depressed water level approaches or reaches the riverbed, it appears that the water recedes from the shoreline as the ship passes, then rushes in to an above-normal level, and finally returns to the normal level after the vessel-induced surface waves are damped.

d. For sediment transport to take place, near-bottom water velocities must exist that are sufficient to overcome a sediment particle's resistance to motion. These water velocities may be caused by ambient river conditions, wind-driven waves, general turbulence, or ship-induced effects and might be enhanced by channel configuration or ice irregularities. During vessel passage, large and rapid changes in river velocity and direction can occur.

e. To analyze the mechanics of sediment transport during vessel passage, two-dimensional near-bottom velocity measurements were made. An example of these measurements is presented in Figure 7-1 for a passage of the *Cason J. Callaway* at Six Mile Point on the St. Marys River. As shown in Figure 7-1, the point of observation was approximately 152 meters (500 feet) offshore in 3 meters

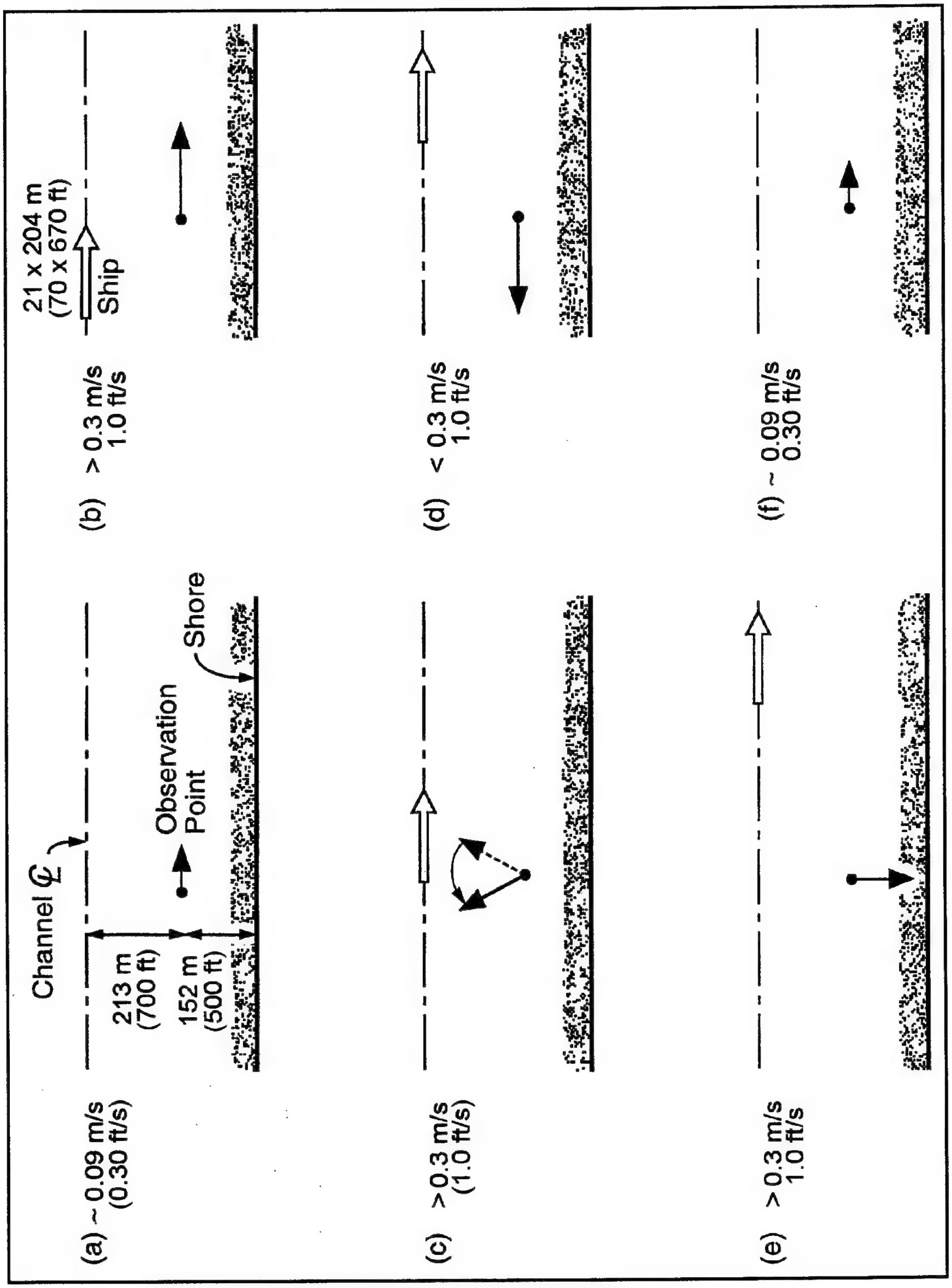

Figure 7-1. Ship-induced water movements

(10 feet) of water, while the navigation track was another 213 meters (700 feet) offshore. The ambient downstream water velocity was approximately 0.1 m/s (0.3 ft/s). The direction of the near-bottom water movement rotated 360 degrees during the passage of the *Callaway,* with velocities in all directions significantly greater than the ambient downstream current.

f. Water level measurements and directional water velocity measurements have been made at a number of locations under various conditions during the passage of ships. A set of water level and velocity measurements is shown in Figure 7-2 that illustrates the trough effect near the shoreline (in this instance, the river level temporarily fell below the base of the staff gage) and the complex velocity pattern that developed at an offshore point because of vessel passage. Velocity direction is indicated as an arrow at any particular point, with the magnitude of the velocity and time as the axes. The velocity meter was located approximately 40 meters (130 feet) from the shore in 0.9 meters (3 feet) of water. The velocities shown were measured within 20 centimeters (8 inches) of the bottom. The water level gage was located near the shore in about 20 centimeters (8 inches) of water. The ship that caused the situation illustrated in Figure 7-2 was the *J. Burton Ayers*, moving upriver near Nine Mile Point on the St. Marys River under ice-free conditions. The *Ayers* is 189 meters (620 feet) long, and has an 18-meter (60-foot) beam, with a midship draft of 7 meters (23 feet). The vessel was traveling at 17 km/hr (10.6 mph) and passed approximately 244 meters (800 feet) from the shore.

g. Figure 7-3 shows ice level changes at three offshore locations near Six Mile Point on the St. Marys River. The ice was approximately 38 centimeters (15 inches) thick. The ship passing the section was the *Seaway Queen,* moving upriver at 13.8 km/hr (8.6 mph). The ship is 219 meters (720 feet) long, with a beam of 22 meters (72 feet) and a midship draft of 5.2 meters (17 feet), and passed (305 meters) 1000 feet offshore. The typical river cross section at this location is shown in Figure 7-4. The two lower curves shown in Figure 7-3 illustrate ice level changes at two different locations on a line approximately normal to the direction of ship movement in different depths of water (labeled E_1 and E_2). The top curve (labeled H_1) shows the ice level change at a point 46 meters (150 feet) upstream on a line parallel to the line containing points E_1 and E_2. The time at which the bow and stern crossed the perpendicular range line (E or H) is indicated on each curve by dashed lines. The figure illustrates the trough effect in different depths of water at differing distances from shore, as well as the movement of the trough with the ship's passage. Note that the time displacement between E_1 and H_1 corresponds to the distance between the two range lines divided by the ship's speed.

h. Figure 7-5 shows ice elevation changes and the associated velocity pattern near the bottom as the *Edward L. Ryerson* passed down river. The ice was 28 centimeters (11 inches) thick. The range line used (E) is the same as that described in Figure 7-3. The ice level and velocity pattern are measured at a location about 91 meters (300 feet) from the shore, where the river depth is about 1.8 meters (6 feet). The ship is 222 meters (730 feet) long, has a beam of 22.8 meters (75 feet) and a draft of approximately 7.9 meters (26 feet), and was traveling at 11 km/hr (7 mph) about 305 meters (1000 feet) offshore. Figure 7-5 illustrates the ice level response to the moving trough and associated velocity pattern for a downbound vessel. Ice level fluctuations as large as 0.8 meters (2.6 feet) have been observed.

i. Three modes of transport of granular bottom sediments have been observed during both ice-covered and ice-free conditions. They are bed load, which is typified by a pattern of slowly migrating sand ripples on the riverbed; saltation load, where individual sand grains move in a series of small arcs beginning and ending at the riverbed; and a process called explosive liquefaction.

(1) Saltation transport has often been observed during the passage of large vessels. This can be explained by the ship-induced velocity increases, examples of which are shown in Figures 7-2 and 7-5.

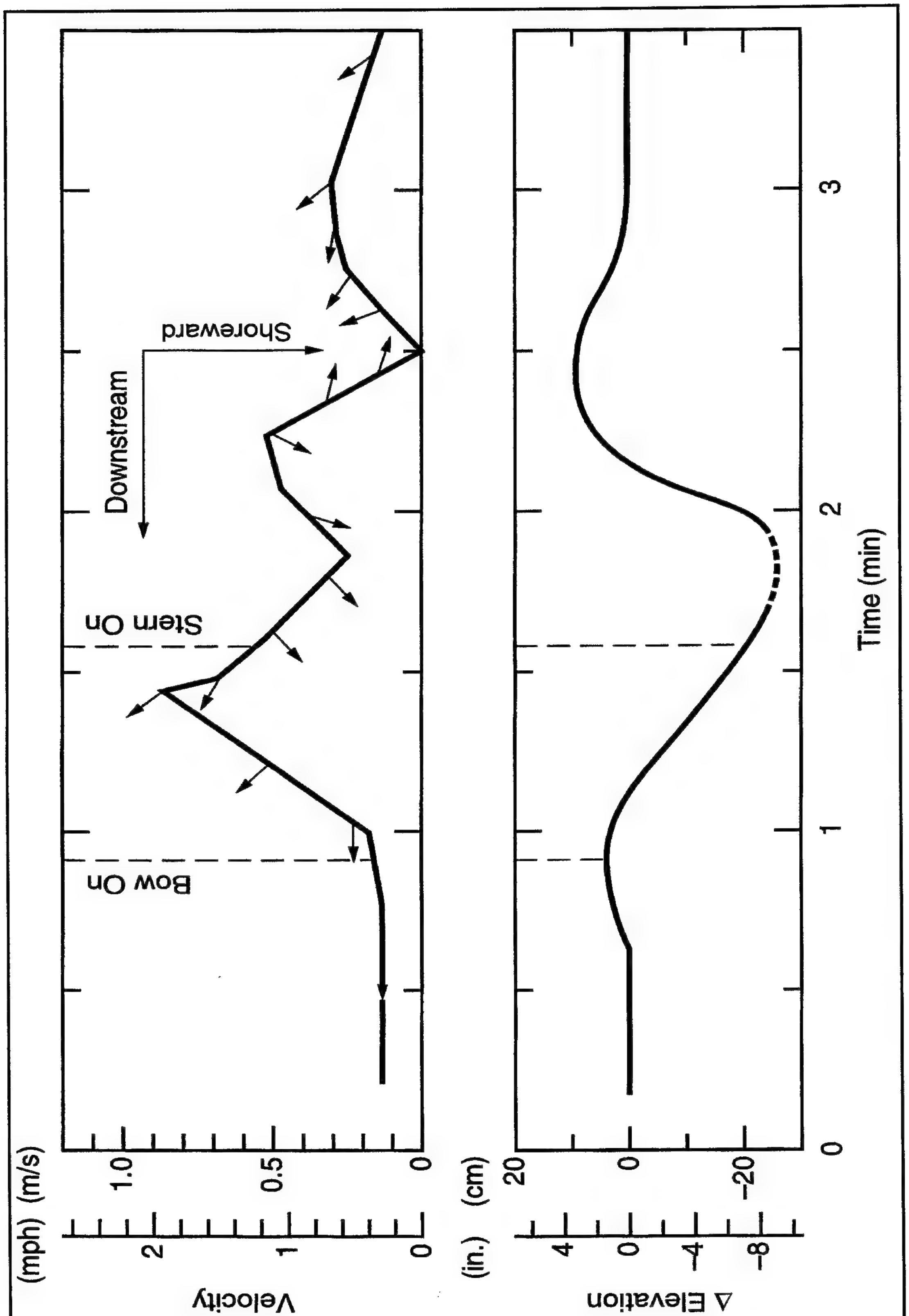

Figure 7-2. River level and near-bottom velocity pattern with upbound ship

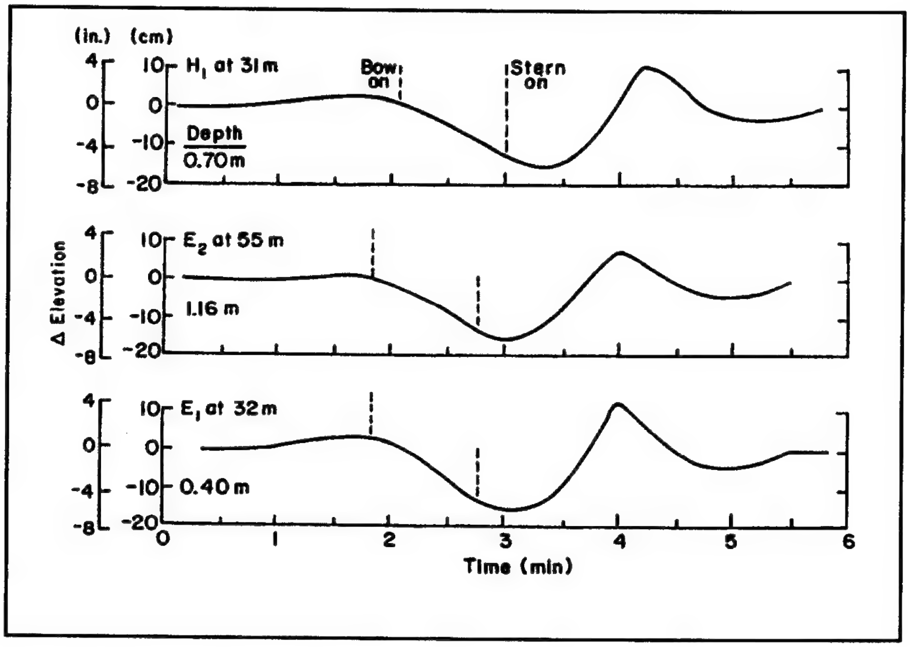

Figure 7-3. Ice level changes with upbound ship

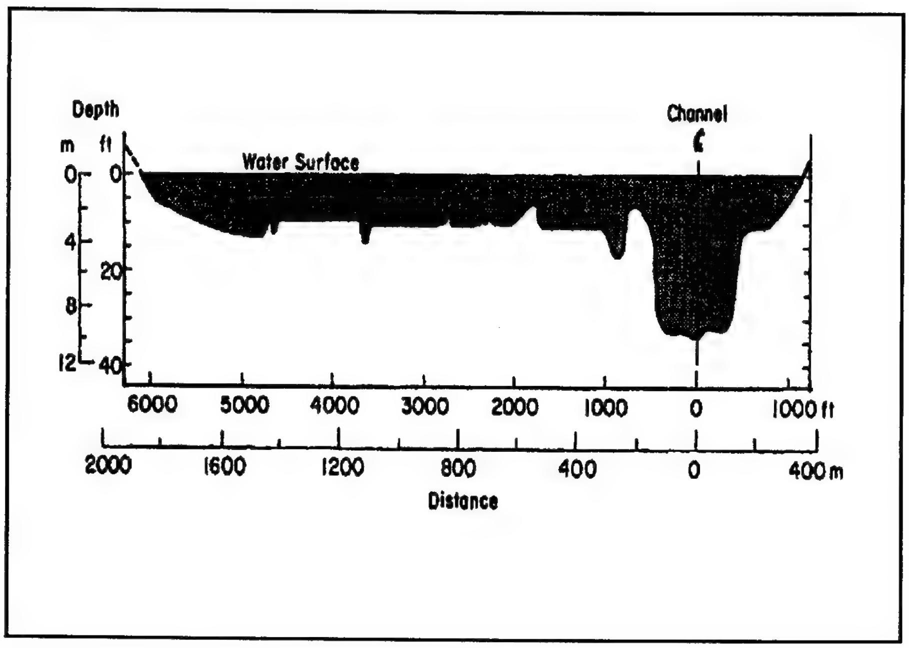

Figure 7-4. Cross section of the St. Marys River near Six Mile Point

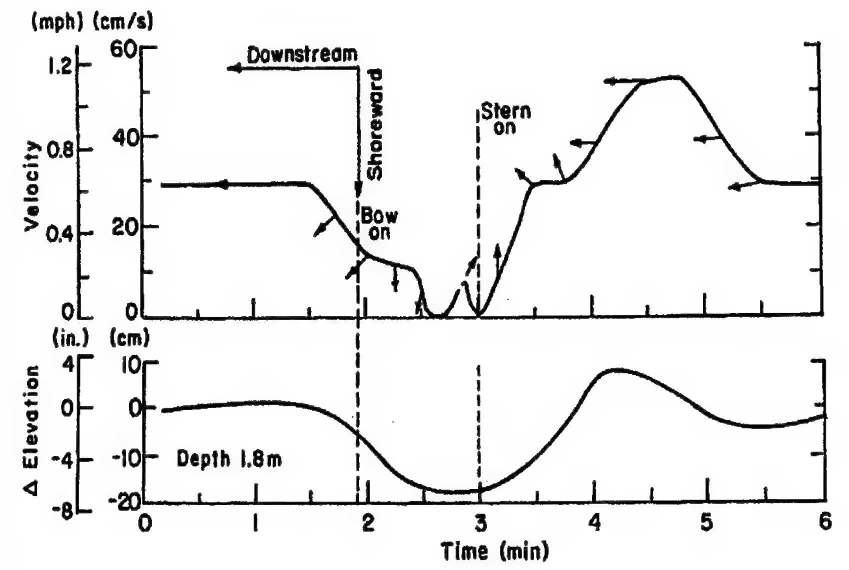

Figure 7-5. River level and near-bottom velocity pattern with downbound ship

(2) On several occasions, explosive liquefaction has occurred during the passage of large, deeply loaded vessels at speeds higher than normal. Divers have observed explosive liquefaction while working in the surf zones of lakes and oceans. It may also be observed from shore as waves break. In the presence of a reasonably horizontal velocity field, the action occurs in two steps. The bed expands upward, immediately followed by a dispersion into suspension mass in the water current. In the absence of a current, the bed simply quakes or expands and individual particles move upward. Bed equilibrium is rapidly reestablished by gravity forces.

j. Since the drawdown and surge mechanism usually sets up water velocities in opposite directions, their effects have a tendency to cancel. However, natural currents or a sloped bottom can act in conjunction with vessel effects to cause a net sediment transport downstream or offshore toward the navigation channel.

k. During winter ice conditions, the passage of the moving trough can cause the grounding of an ice cover in shallow water and nearshore areas, and nearshore cracks in the ice may develop running roughly parallel to the water depth contours. With recurring moderate water level fluctuations, these hinge cracks do not completely refreeze and can provide an ice-movement relief mechanism. Continuing vertical and horizontal movement of the ice cover may cause the accumulation of ice debris (which resembles pressure ridges) at these active cracks. Depending upon the characteristics of crack formation, ice dams extending to the riverbed may develop at the cracks (Figure 7-6).

l. The mechanism described above may have effects beyond shoreline erosion. Large areas of grounded ice that result from the packing of brash ice under the ice cover or increased frazil production because of increased open-water areas may have an impact on benthic environments and may transmit ship-induced vibrations to the shore and shore structures. The reported effects of these vibrations range from aesthetically disturbing to structurally damaging. In wetlands or shoaling areas, damage may occur

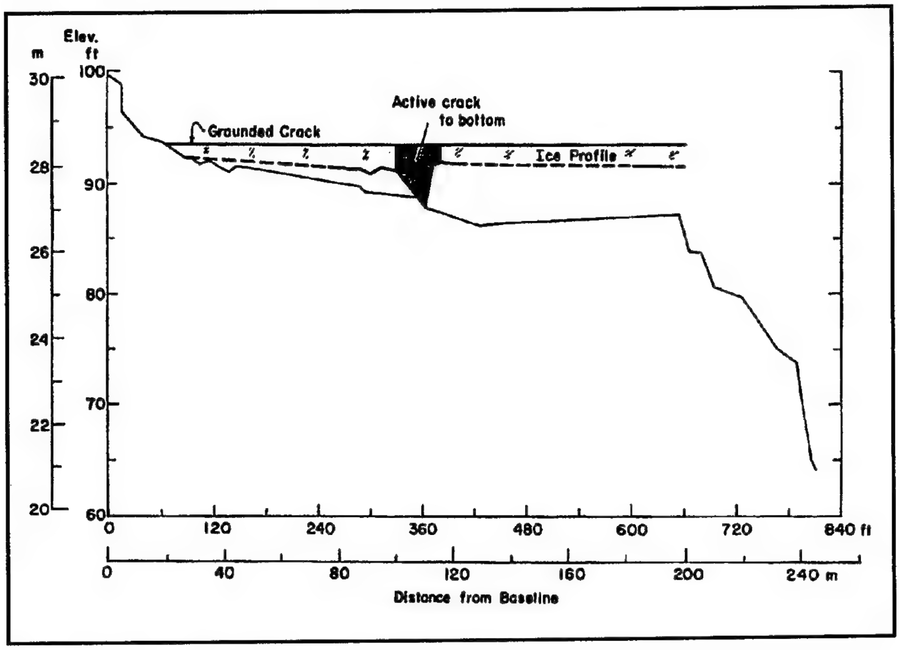

Figure 7-6. Active crack profile

even though erosion is negligible. In shallow water, ship-induced velocity and water level changes could be large, possibly disrupting vegetation by water and ice movement. An ice cover might even ground and directly strike the bed during vessel passage. Rapid water pressure changes might also be significant.

m. When a large enough ship-induced moving trough passes through a shallow water area, the movement of bottom sediment may disrupt benthic environments, and the translatory movement of the water has been observed to cause water, sediment, vegetation, and even small fish to be sprayed up through the cracks and onto the ice. During a specific vessel passage, about a dozen fish of various species, ranging in length up to about 15 centimeters (6 inches), were washed through a nearshore crack and onto the ice. It is possible that other smaller organisms went unnoticed.

n. Disruption of an ice cover may also have some as yet undefined effect on ice movement and damage caused by natural ice forces. In the case of relatively ice-free rivers, such as the Detroit or the St. Clair, the disruption of an ice cover on the lakes upstream may allow large quantities of ice to enter the rivers. This can cause bottom scour and ice pile-up at bends and the upstream ends of islands. The large forces that may result from such ice runs can also pose a special threat to shore protection structures.

o. In most coastal areas, natural shoreline modification forces, such as waves and currents, are far more significant than any vessel-related effects, and generally the shipping lanes do not come near enough to the shore for vessels to have a noticeable effect. In some protected areas this may not be true. After disruption of a natural ice cover, ice movement problems could be particularly important in coastal areas where significant wind exists to push the ice.

7-4. References

a. Required publications.
None.

b. Related publications.

Wuebben 1995
Wuebben, J.L., ed. 1995. *Winter Navigation on the Great Lakes: A Review of Environmental Studies*, CRREL Report 95-10, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Chapter 8
Bearing Capacity of Floating Ice

8-1. Introduction

When a river, lake, or sea is subjected to air temperatures below the freezing point for an extended period of time, an ice cover forms, whose thickness depends on the intensity of this freezing temperature, its duration, and other factors. This subject is discussed in detail in Chapter 2 of this manual. The thickness of this ice cover may be measured mechanically by a crew that operates on the ice cover. It may also be measured remotely, say from an airplane or balloon, by means of electromagnetic waves. This chapter discusses the bearing capacity of floating ice and the methods of predicting it.

8-2. Bearing Capacity of Ice Blocks

First, consider an ice block of uniform thickness floating in water (Figure 8-1). Because the specific weight of ice is less than that of water, the ice block floats. It may also carry an additional load P.

a. To determine the bearing capacity of this floating block, subjected centrally to a static load P, consider its vertical equilibrium before it is totally submerged, as shown in Figure 8-1. The equilibrium equation, for $z \leq h$, is

$$P + Ah\,\gamma_i = Az\,\gamma_w \tag{8-1}$$

where

P = vertical resultant of the load

A = horizontal area of the ice block

γ_w = specific weight of water

γ_i = specific weight of ice.

The other symbols are defined in Figure 8-1. Bearing capacity is reached when z approaches h. Substituting the limiting case $h = z$ into Equation 8-1 yields

$$P_{max} = Ah\,(\gamma_w - \gamma_i). \tag{8-2}$$

This is the largest load the ice block can carry. For larger loads P, the block will sink. It may be of interest to note that without the load P, the submerged depth of the block, according to Equation 8-1, is

$$z_o = h\frac{\gamma_i}{\gamma_w}. \tag{8-3}$$

b. Following are two illustrative examples of Equation 8-2.

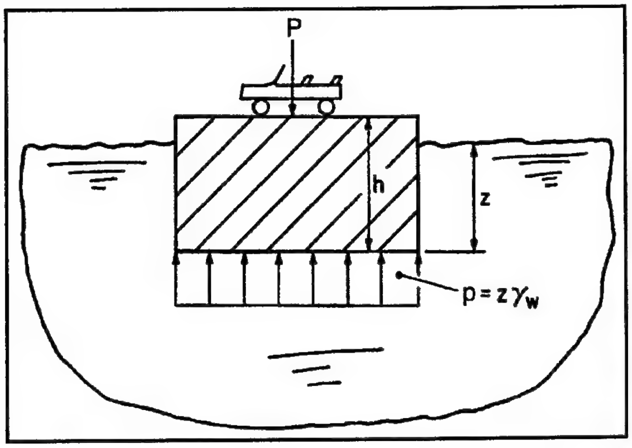

Figure 8-1. Floating ice block with a centrally placed load *P*

(1) Determine the bearing capacity of an ice block of thickness h = 3 feet (0.9 meters) and a surface area A = 100 ft^2 (9.29 m^2) for a centrally placed static load P. According to Equation 8-2, with γ_w = 62.4 lb/ft^3 (1000 kg/m^3) and γ_i = 57.3 lb/ft^3 (918 kg/m^3), the largest weight the ice block can carry is

$$P_{max} = 100 \times 3 \times (62.4 - 57.3) = 1530 \text{ lb.}$$

In SI units

$$P_{max} = 9.29 \times 0.9 \times (1000 - 918) = 686 \text{ kg.}$$

(2) For an ice block of constant thickness h = 2 feet (0.6 meters), determine the surface area A needed to carry a centrally placed load of P = 3000 pounds (1361 kilograms). From Equation 8-2 it follows that the required area is

$$A_{req} \geq \frac{P}{h(\gamma_w - \gamma_i)}.$$

With γ_w = 62.4 lb/ft^3 (1000 kg/m^3) and γ_i = 57.3 lb/ft^3 (918 kg/m^3), it follows that

$$A_{req} \geq \frac{3000}{2(62.4 - 57.3)} = 294 \text{ ft}^2 \text{ (or 27.7 m}^2 \text{ in SI units).}$$

For example, a square area of 17 × 17.3 (5.2 × 5.3 meters) will achieve this aim.

c. When the resultant of the load is not centrally placed on the ice block, the ice block will tilt. This will result in a linearly varying pressure p at the bottom surface of the block. The bearing capacity for this case may be determined as done previously, except that now, in addition to vertical equilibrium, the moment equilibrium has to be considered. Note that when the eccentricity of the load resultant exceeds a certain limit, namely when the loading moment is larger than the restoring moment, the ice block will tip over. When the load is dynamic the analysis is more involved. Then, the equations of motion for the ice block have to be coupled with the dynamic equations for the fluid base.

8-3. Bearing Capacity of Ice Covers for Loads of Short Duration

When the dimensions of the ice plate are very large compared to its thickness, the ice cover is relatively flexible in the vertical direction and a vertical load *P* will deflect the plate, as shown in Figure 8-2. Thus, in addition to the constant pressure p_0 caused by the uniform weight of the ice cover, there will also occur a variable pressure $p(x,y)$ caused by the boat effect of the deflected cover (Ashton 1986).

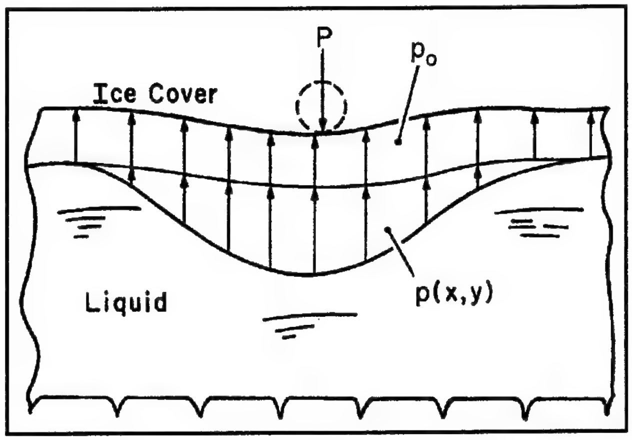

Figure 8-2. Deflection of large ice plate from vertical load *P*

a. As is well known, sufficiently large loads will break through the ice. For this problem, the bearing capacity of the ice cover depends on the strength of the cover to resist the vertical deformations.

b. To date there is no generally accepted method for calculating the bearing capacity of flexible ice covers. One of the reasons is that ice is a complex material, complicated further by the fact that the bottom part of a floating cover is near the melting temperature. Another reason is a lack of researcher interest in break-through tests on frozen lakes or rivers, especially at low temperatures. Still another is the general lack of coordination between the theoretical and empirical testing efforts conducted throughout the world. In the meantime, there is a need for estimating the bearing capacity of large ice covers subjected to a variety of loads. To achieve this, a number of approaches used in various countries are presented and discussed.

8-4. Experience Values

Individuals who often use ice covers for transportation develop a knowledge of the bearing capacity of ice covers of given thickness and quality through experience. To enable an interested party to make a rough estimate of the ice thickness needed for safe movement of people and vehicles, Table 8-1 is included. In determining the effective ice thickness to be used with Table 8-1, any thickness of "snow" ice (i.e., ice that is white owing to entrained air bubbles) should be set as equivalent to half that thickness of clear "black" ice. For example, if the measured thickness of the ice cover is 76.2 centimeters (30 inches), of which 25.4 centimeters (10 inches) is snow ice, the effective ice thickness should be considered as 50.8 + 25.4/2 = 63.5 centimeters (20 + 10/2 = 25 inches).

Table 8-1
Approximate Ice Load-Carrying Capacity (Note: Read the text before using table.)

Type of Vehicle	Total Weight†, Metric tons (tons)	Necessary Ice Thickness* at Average Ambient Temperature for Three Days - cm (inches): 0 to -7 °C (32 to 20 °F)	-9 °C and Lower (15°F and Lower)	Distance Between Vehicles m (ft)
Tracked	6.6 (6)	25.4 (10)	22.9 (9)	15.2 (50)
	11.0 (10)	30.5 (12)	27.9 (11)	19.8 (65)
	17.6 (16)	40.6 (16)	35.6 (14)	24.4 (80)
	22.0 (20)	45.7 (18)	40.6 (16)	24.4 (80)
	27.6 (25)	50.8 (20)	45.7 (18)	30.5 (100)
	33.1 (30)	55.9 (22)	48.3 (19)	35.1 (115)
	44.1 (40)	63.5 (25)	55.9 (22)	39.6 (130)
	55.1 (50)	68.6 (27)	63.5 (25)	39.6 (130)
	66.1 (60)	76.2 (30)	71.1 (28)	45.7 (150)
Wheeled	2.2 (2)	17.8 (7)	17.8 (7)	15.2 (50)
	4.4 (4)	22.9 (9)	20.3 (8)	15.2 (50)
	6.6 (6)	30.5 (12)	27.9 (11)	19.8 (65)
	8.8 (8)	33.0 (13)	30.5 (12)	32.0 (105)
	11.0 (10)	38.1 (15)	35.6 (14)	35.1 (115)

* Freshwater ice.
† When the temperature has been 0 °C (32 °F) or higher for a few days, the ice is probably unsafe for any load.

8-5. Empirical Methods

An often used formula for single vehicles is

$$P = Ah^2 \tag{8-4}$$

where P is the allowable load, h is the effective ice cover thickness, and A is a coefficient that depends on the quality of the ice, the ice temperature, the geometry of the load, the kind of units used, and the factor of safety. To ensure safe movement of single vehicles crossing lake or river ice at temperatures below 0°C (32°F), the straightforward and practical formulas $P = h^2/16$ or $h = 4\sqrt{P}$ have been used for decades. These formulas are for English units in which P is in tons and h is in inches. Although not strictly equivalent, similar practical formulas for SI units are $P = h^2/100$ or $h = 10\sqrt{P}$, where P is in metric tons (1000 kg) and h is in centimeters, and $P = h^2$ or $h = \sqrt{P}$, where P is in meganewtons and h is in meters. These formulas are all for black ice below 0°C (32°F), and appropriate adjustments to thicknesses to account for snow ice should be computed as in paragraph 8-4. The following are illustrative examples of Equation 8-4.

a. Determine the allowable load of an ice cover with the smallest ice thickness h = 25.4 centimeters (10 inches).

$$P = \frac{h^2}{16} = \frac{10\times10}{16} = 6.25\ tons.$$

In metric units, this is

$$P = \frac{h^2}{100} = \frac{25.4 \times 25.4}{100} = 6.45 \times 10^3 \text{ kilograms (6.45 metric tons)}.$$

b. Determine the smallest ice thickness needed to safely carry one person of weight P = 200 lb = 0.1 ton (90.7 kilograms = 0.0907 metric ton).

$$h = 4\sqrt{P} = 4\sqrt{0.1} = 1.26 \text{ inches}$$

Expressed in metric units, the required thickness is

$$h = 10\sqrt{P} = 10\sqrt{0.0907} = 3.0 \text{ centimeters}.$$

8-6. Method Based on the Theory of Elastic Plates

An analytical method for determining the bearing capacity of an ice cover for loads of short duration is based on the elastic bending theory of thin plates in conjunction with a crack criterion. The method consists of the following three steps

- Determination of the maximum stress σ_{max} in the floating plate attributable to a given load.

- Determination of the load P_{cr} at which the first crack occurs, utilizing the crack criterion $\sigma_{max} \leq \sigma_f$, where σ_f is the failure stress.

- Correlation of P_{cr} with the breakthrough load P_f. This step is needed because, according to field tests for various plate and load geometries, the occurrence of the first crack does not cause breakthrough.

The failure stress σ_f is usually obtained by loading a floating ice beam, cut out from the ice cover under consideration as shown in Figure 8-3, to failure and then by computing the largest bending stress at which it failed.

a. With the equation $D\nabla^4 w + \gamma w = q$ for the response of a homogeneous ice cover, in which w is its deflection, subjected to a uniform load q over a circular area, as shown in Figure 8-4, in conjunction with the crack criterion $\sigma_{max} < \sigma_f$,

$$P_{cr} = \left(\frac{1}{3(1 + \nu)C(\alpha)}\right)\sigma_f h^2 \qquad (8\text{-}5)$$

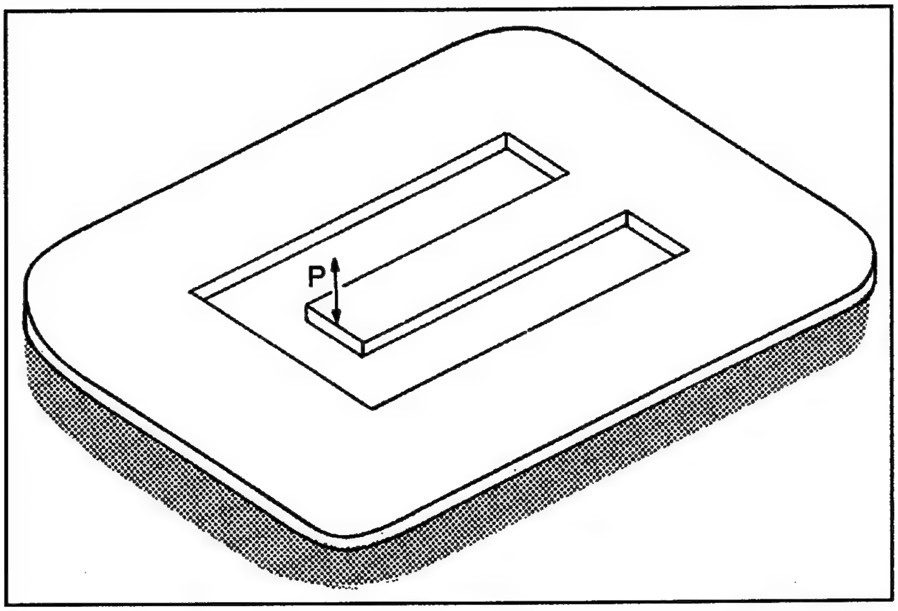

Figure 8-3. Stress test of floating ice beam

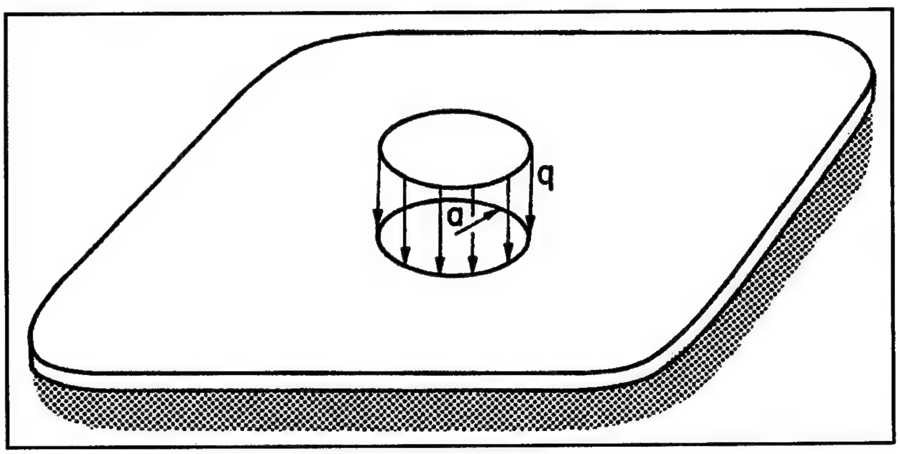

Figure 8-4. Homogeneous ice cover subjected to a uniform load over a circular area

where

h = ice cover thickness

ν = Poisson's ratio of the ice cover

a = radius of the loaded area subjected to the uniform load

$q = P/(\pi a^2)$

$\alpha = a/(D/\gamma)^{1/4}$

γ = specific weight of the liquid base

$D = Eh^3/[12(1 - \nu^2)]$

E = Young's modulus of the ice cover

∇^4 = biharmonic operator, e.g. $(\partial^4/\partial x^4 + 2\partial^4/\partial x^2\partial y^2 + \partial^4/\partial y^4)$ in Cartesian coordinates

$C(\alpha)$ = given in Figure 8-5.

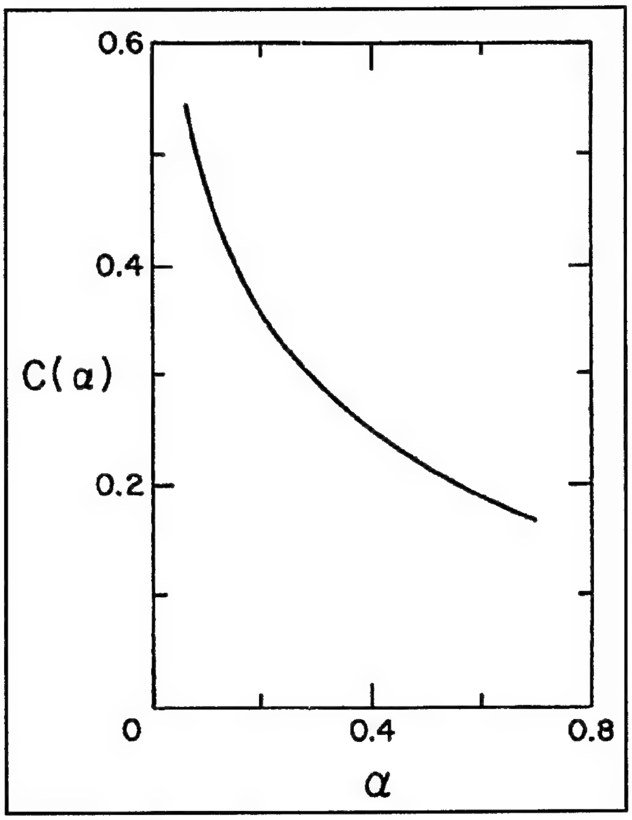

Figure 8-5. *C*(α) for Equation 8-5

b. To demonstrate the use of Equation 8-5, consider an ice cover with h = 30.5 centimeters (12 inches), E = 3.45 GPa (500,000 lbf/in.^{2}), ν = 0.34, for a circular load distribution with radius a = 102 centimeters (40 inches). According to Figure 8-6, the resulting $(D/\gamma)^{1/4}$ = 554 centimeters (218 inches) and hence α = 40/218 (or 102/554) = 0.18. According to Figure 8-5, the corresponding $C(\alpha)$ = 0.38. Thus

$$P_{cr} = \left(\frac{1}{3(1 + 0.34)0.38} \right) \sigma_f h^2 = 0.65\, \sigma_f h^2 .$$

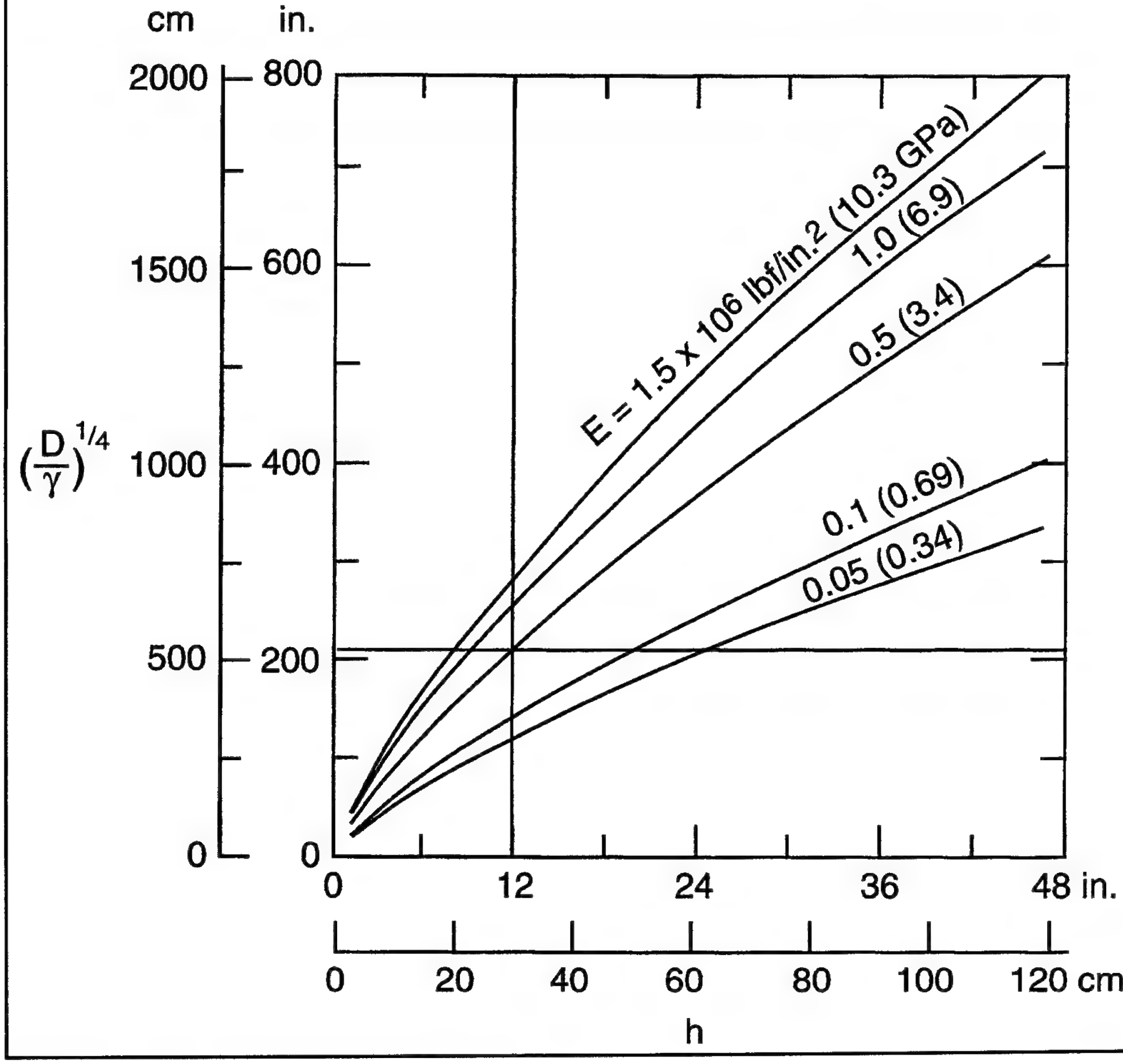

Figure 8-6. Graph required to solve Equation 8-5

8-7. Bearing Capacity of Ice Covers for Loads of Long Duration

For loads that do not cause an instantaneous breakthrough, the ice cover deforms at first elastically, and then with time it continues to deform by creep, especially in the vicinity of the load. Depending upon the load intensity and geometry, as well as upon the ice cover properties, the resulting time displacement graph may be of the type shown in Figure 8-7. In the case of the upper curve (I), although the ice cover was able to carry the load immediately after the load was placed on it, there exists a "time to failure" t_f at which the load breaks through the cover. Attempts to analyze problems of this type have not been conclusive to date. In the absence of a reliable method for predicting the bearing capacity of ice plates subjected to loads of long duration (storage of equipment, parking of vehicles, and airplanes), Figure 8-8 is presented for estimates. Note the drop of the breakthrough load with time. Thus, a stored item that is safe when placed on the ice cover may break through after a certain time period t_f.

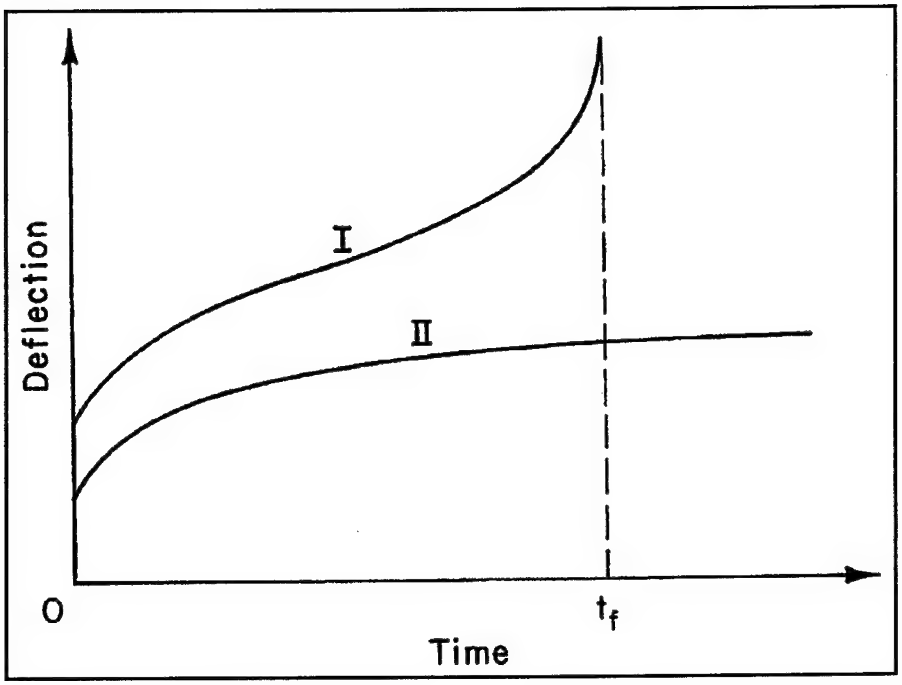

Figure 8-7. Time-displacement graph of ice deformity

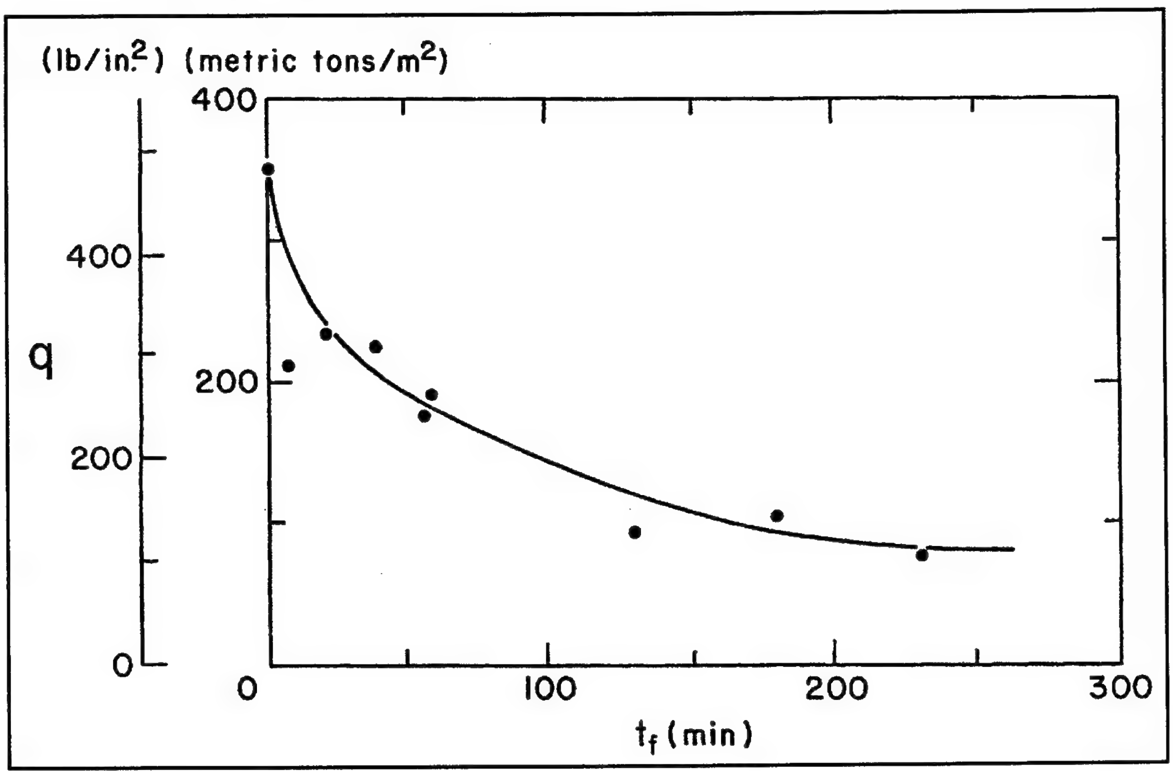

Figure 8-8. Bearing capacity reduction for loads of long duration

8-8. Other Considerations

Practically, there are a few things one should be aware of when operating on the ice. Cracks are almost always present because of thermal expansion. Most of these are called "dry cracks" because they do not go to the bottom of the ice sheet (note the concept that all thermal expansion is in the upper portion of the sheet because the bottom is always at 0°C [32°F]). These dry cracks do not have an appreciable effect on bearing capacity. However, wet cracks that do penetrate the entire sheet should be approached at 50 percent acceptable load and one should try to cross them at an angle near 90 degrees.

a. When parked, i.e., the long-term load situation, one should look for any signs of water coming up through the ice and beginning to flood the area. If this occurs, *MOVE*, because breakthrough is almost inevitable; this water is an additional load.

b. Throughout the preceding paragraphs, we have stressed the importance of temperature and inferred daily average air temperatures. This was done because this is the information available, but it is the ice temperature that is important. So, remember that snow cover, as an insulation, slows ice temperature change. Also, experience has shown that an added safety factor is necessary when there has been a recent big drop in air temperature. Apparently, this causes a thermal shock leading to additional cracking. Many accidents to experienced operators have occurred after a rapid drop in air temperature.

8-9. References

a. Required publications.
None.

b. Related publications.

Ashton 1986
Ashton, G.D., ed. 1986. *River and Lake Ice Engineering*, Water Resources Publications, Littleton, Colorado.

Chapter 9
Model Tests

9-1. General

Small-scale laboratory modeling of hydraulic structures (locks, dams, weirs, spillways, etc.) and vessels under open-water conditions is now common, and the modeling laws, criteria, and techniques are well established. The presence of ice adds serious complications to small-scale modeling because it adds a boundary at the top surface of the water body having different surface characteristics than the bed of the waterway. Moreover, whenever the mechanical properties of ice affect the problem under study, these must be duplicated in the model. The basic principle of dynamic similitude or modeling is to reproduce in the model the forces that govern the problem under consideration (gravity forces, inertia forces, viscous forces, shear forces, mechanical forces, etc.) in such a way that the ratio between any two forces in the model is equal to the corresponding ratio in the prototype. Except for a few cases, all these forces usually play some role in the actual physical phenomena of interest. Thus, strict adherence to the principle of dynamic similitude will lead to the conclusion that the phenomena can only be studied at full scale. It then becomes necessary to relax the principle of similitude, and to choose to model exactly only those forces that primarily affect the problem under consideration. Simultaneously, the "scale effects," or errors introduced by imperfect modeling of the secondary forces, are held to a minimum by judicious model design. Therefore, it is important at the outset to correctly identify the primary forces that govern a particular phenomenon before attempting to study it in a physical model. This must be done to decide whether the necessary modeling techniques are available and how the model data can be extrapolated to full scale. In the present state of the art of ice modeling, phenomena that are strongly affected by heat transfer, e.g., refreezing of broken ice, icing of structures and the like, are not amenable to physical modeling.

9-2. Modeling Broken Ice

In phenomena that do not involve a solid ice sheet, but only ice floes, the main forces to consider are usually gravity forces, but also may include buoyancy forces, inertia forces, and possibly shear forces ascribable to water flowing underneath the stationary floes (e.g., ice held at a retaining structure such as an ice boom). If ice-on-ice friction is not considered to be critical, artificial ice floes can be used instead of real ice floes in the model, as long as the density of the material is equal to that of ice (e.g., polyethylene). The model study can then be made in an unrefrigerated facility with significant reduction in cost. An example of such a study is found in Calkins et al. (1982).

9-3. Modeling Sheet Ice

When the phenomenon to be studied involves the failure or breaking of an initially intact ice cover (e.g., ice forces on structures), the mechanical properties of ice (bending strength, crushing strength, shear strength, and ice friction) become important and must be properly modeled in the laboratory.

a. Model ice grown from a solution of salt or urea in water has been developed that can yield the required properties, as long as the model scale is greater than some limiting value. This limiting scale will depend upon the mode of failure of the ice sheet. (For example, the limiting scale is approximately 1:40 for ice failing in bending.) A refrigerated facility is necessary for this type of modeling. Discussion of a model study conducted in a refrigerated facility is given in Deck (1985) and in Gooch and Deck (1990).

b. Some artificial materials have been developed that are claimed to reproduce the properties of real ice, but their composition is proprietary, their handling is often messy, and even though they can be used in a warm environment, the cost of the experiments is similar to those in refrigerated facilities.

9-4. Model Calibration

Once a modeling technique has been chosen and the physical model built, it should be calibrated or verified. This process usually consists of the following steps: adjustment of bed roughness to reproduce the water surface profile without ice (this is the normal model verification for conventional hydraulic models); verification of head losses with simulated ice cover for known field conditions; and verification of the similitude of ice processes for known field conditions, such as ice breakup, ice drift pattern, and velocity. Even if this last verification is only qualitative, it is necessary to ascertain that the model is simulating observed natural phenomena. The objective of the calibration of a hydraulic model is to reproduce field conditions under more or less normal conditions, so that the model can be used to predict the effects of *abnormal* conditions or those produced by man-made changes with a good degree of confidence. In an ice–hydraulic model, it is not sufficient to reproduce water levels at various discharges as in a conventional hydraulic model. The ice phenomena also have to be correctly simulated. Many ice phenomena are not fully understood. If they are not carefully observed and documented at the particular field site to be modeled, it is unlikely that they can be simulated correctly in the model.

9-5. Model Distortion

While undistorted models, i.e., models with the same scale in both the horizontal and vertical directions, are by far preferable, distorted hydraulic models may have to be used when modeling long reaches of wide rivers. This is accomplished by exaggerating the vertical scale relative to the horizontal scale. The distortion does impose, however, a reevaluation of the roughness to be used in the model to correctly simulate the head losses occurring in nature. The distortion affects the scale of the thickness and mechanical properties of the ice to be formed in the model, as well as the extrapolation of the model test results to full-scale conditions. The distortion ratio, i.e., the ratio of vertical scale to horizontal scale, should be kept to a minimum and, under the present state of the art, no greater than 4 to 1.

9-6. Considerations in Choosing Modeling

While proper physical hydraulic modeling must follow some basic scientific and engineering principles, it still remains as much an art as a science. This is even more true when ice effects are involved. In this regard, the experience of the engineer in charge of a model study is a critical ingredient to the success of the study and to the reliability of its results. Physical modeling can be a very powerful tool in deciding among various potential designs for a project or among proposed solutions to a particular problem, in optimizing an initial design, in providing rational answers to objections to a proposed design or project, and in detecting potentially undesirable effects of a proposed design or solution, which may not have been foreseen otherwise, or not predicted by numerical modeling. While a physical model study often is a costly endeavor, when properly conducted, it can point the way to design or construction savings that often will more than offset its cost.

9-7. References

a. Required publications.
None.

b. Related publications.

Calkins et al. 1982
Calkins, D., D. Deck, and D. Sodhi. 1982. *Hydraulic Model Study of Port Huron Ice Control Structure*, CRREL Report 82-34, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Deck 1985
Deck, D. 1985. *Cazenovia Creek Physical Ice Model Study*, Report to U.S. Army Engineer District, Buffalo, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire (unpublished).

Gooch and Deck 1990
Gooch, G., and D. Deck 1990. *Model Study of the Cazenovia Creek Ice Control Structure*, Special Report 90-29, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Part II: Ice Jams and Mitigation Measures

Chapter 10
Ice Jam Flooding in the United States

10-1. General

Flooding and flood-related events cause greater damage and more fatalities than any other natural disaster. About 80 percent of all presidential disaster declarations are the result of flooding (Federal Emergency Management Agency 1992a). Flood damages averaged $3.3 billion and flood-related fatalities averaged about 100 annually over a recent 10-year period (U.S. Army 1993, 1994). The most common type of flood is the result of a major rainfall or snowmelt. A second type of flood happens suddenly, as in the case of dam failures or intense rainfall that generates a flash flood. A third category of flood results from an ice or debris jam. Flood stages during an ice jam (Figure 10-1) can increase more rapidly and attain higher levels than those associated with open-water conditions. Ice jam flooding may take place outside the regulatory floodplain, often when the river flow would not otherwise cause problems. Many laws and regulations have been developed to reduce national vulnerability to flooding. Most American communities have floodplain regulations designed to prevent future development in areas subject to conventional open-water flooding. Some communities are protected by structural controls, such as dikes, levees, and flood control dams. Mitigation measures specifically designed to protect against ice jam flooding are used less commonly.

10-2. Ice Jam Flooding

In many northern regions, ice covers the rivers and lakes annually. The yearly freezeup and breakup commonly take place without major flooding. However, some communities face serious ice jam threats

Figure 10-1. Ice jam flooding

every year, while others experience ice-jam-induced flooding at random intervals. The former often have developed emergency plans to deal with ice jam problems, but the latter are often ill-prepared to cope with a jam. In a 1992 survey, Corps District and Division offices reported ice jam problems in 36 states, primarily in the northern tier of the United States (Figure 10-2). However, even mountainous regions as far south as New Mexico and Arizona experience river ice. Of the 36 states, 63 percent reported that ice jams occur frequently, and 75 percent rated ice jams as being serious to very serious (White 1992). Ice jams affect the major navigable inland waterways of the United States, including the Great Lakes. A study conducted in Maine, New Hampshire, and Vermont identified over 200 small towns and cities that reported ice jam flooding over a 10-year period (U.S. Army 1980). In March 1992 alone, 62 towns in New Hampshire and Vermont reported ice jam flooding problems after two rainfall events. Table 10-1 lists some of the major ice jams recently recorded.

Table 10-1
Recent Major Ice Jams in the United States

Place	Date	Type (Damages)
Montpelier, Vermont	March 1992	Breakup ($5 million)
Allagash, Maine	April 1991	Breakup ($14 million)
Salmon, Idaho	February 1984	Freezeup ($1.8 million)
Port Jervis, New York/ Matamoras, Pennsylvania	February 1981	Breakup ($14.5 million)
Mississippi River/ Missouri River Confluence	December 1989	Breakup (>$20 million)

a. Characteristics of ice jams and ice jam flooding. Because ice jam floods are less common and more poorly documented than open-water floods, it is more difficult to characterize these events compared to open-water flooding. In addition, because of the complex processes involved in the formation and progression of ice jams and the highly site-specific nature of these jams, these events are more difficult to predict than open-water flooding. The rates of water level rise can vary from feet per minute to feet per hour during ice jam flooding. In some instances, communities have many hours of lead time between the time an ice jam forms and the start of flooding. In other cases, the lead time is as little as 1 hour. Although the actual time of flooding may be short compared to open-water floods lasting days to weeks, significant damage can result. The winter weather conditions often prevalent when ice jams occur also add to the risks and damages associated with ice jam flooding.

b. Example from Montpelier, Vermont, 1992. In March 1992, an ice jam developed at 0700 in Montpelier, Vermont. By 0800 the downtown area was flooded (Figure 10-3). During the next 11 hours, the business district was covered with an average of 1.2 to 1.5 meters (4 to 5 feet) of water. The flood happened so quickly that there was not sufficient time to warn residents so that they could protect their property and possessions. Even after water levels dropped, damage related to the flooding continued as cold weather caused freezing of wet objects. Damages of less than 1 day were estimated at $5 million (Federal Emergency Management Agency 1992b).

10-3. Ice Jam Flood Losses

a. Loss of life. Ice jam flooding is responsible for loss of life, although the number of fatalities in the United States is considerably less than those from open-water flooding. In the last 30 years, at least seven people have died as a result of ice jam flooding. Six of the deaths were attributed to rescue

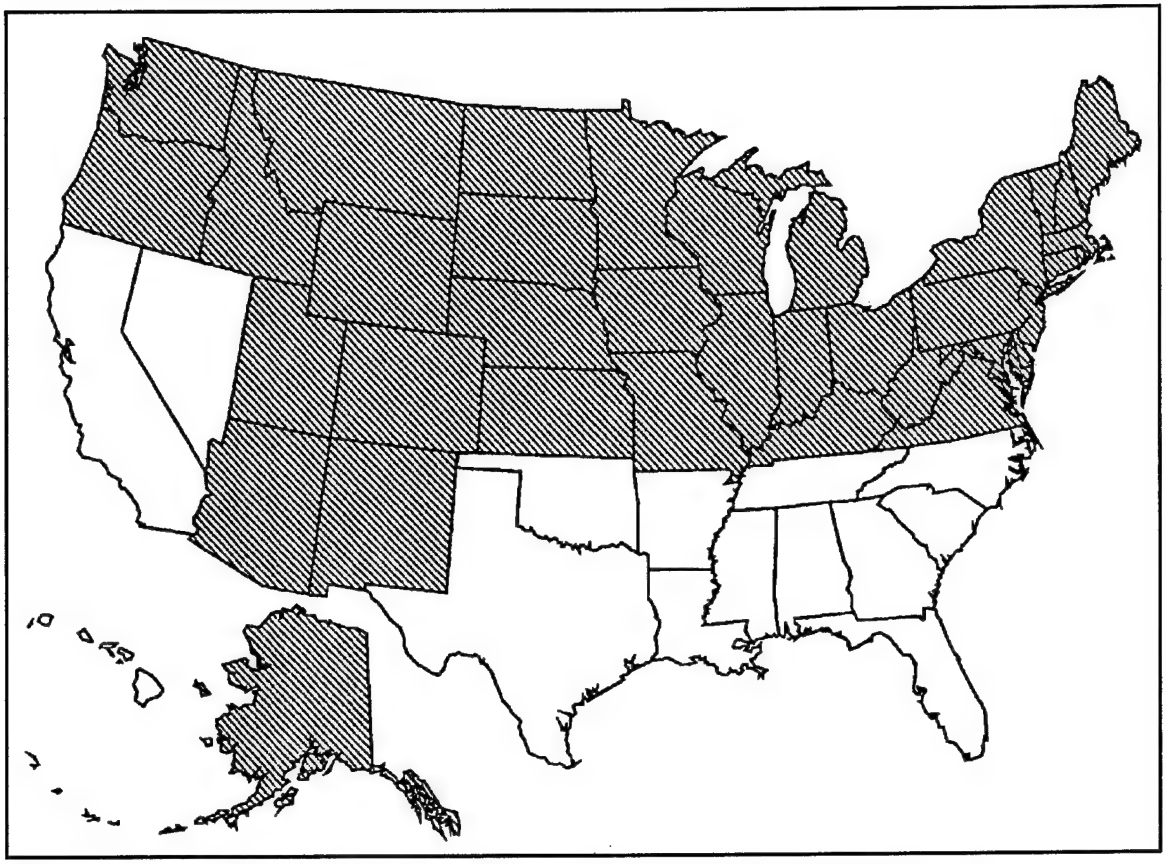

Figure 10-2. Ice jam flooding occurs in shaded states

attempts; the other death occurred from injuries sustained when a basement wall collapsed because of pressure from flood waters and ice.

b. Dollar costs. Ice jams in the United States cause approximately $125 million in damages annually, including an estimated $50 million in personal property damage and $25 million in operation and maintenance costs to Corps navigation, flood control, and channel stabilization structures.

c. Interference with navigation. Ice jams have suspended or delayed commercial navigation, causing adverse economic impacts (Figure 10-4). Although navigational delays are commonly short, they may result in shortages of critical supplies, such as coal and industrial feedstocks, and lead to large costs from the operation of idle vessels (U.S. Army 1981). Ice jams sometimes cause damage to navigation lock gates. Other chapters of this manual provide detailed information on the effects of ice on navigation and the range of strategies to mitigate the effects.

d. Reduced hydropower production. Ice jams also affect hydropower operations, stopping hydropower generation by blocking intakes, causing high tailwater, making reduced discharge necessary, or damaging intake works (Figure 10-5). Lost power revenue attributable to such shutdowns can be substantial.

a. Winooski River

b. Downtown area

Figure 10-3. Views of Montpelier, Vermont, ice jam (March 1992)

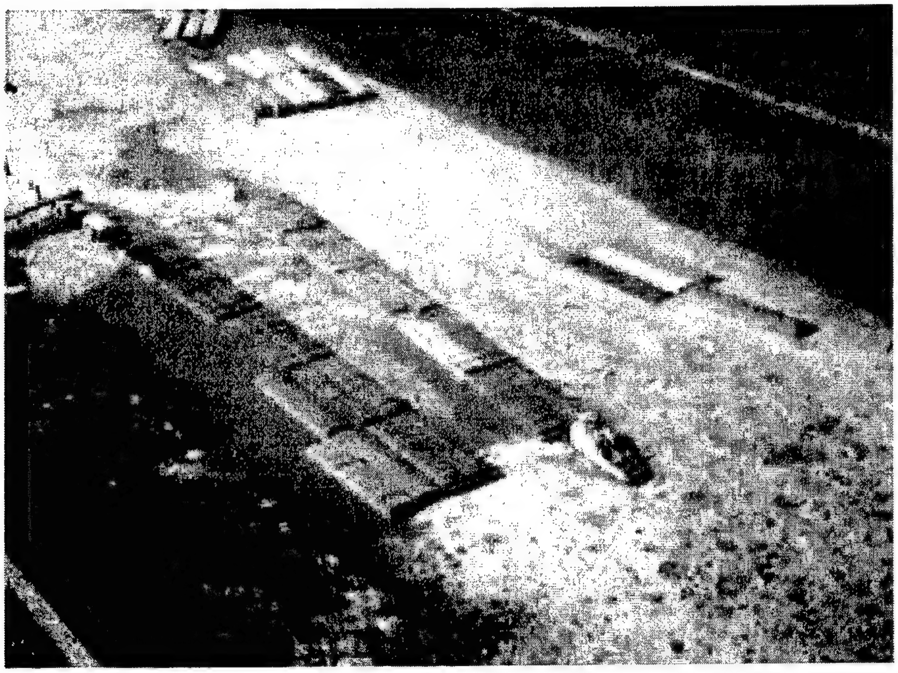

Figure 10-4. Towboats and barges in ice

e. Channel erosion and damage to channel training structures. The presence of an ice jam can result in scouring and river bed and bank erosion that may lead to bridge or river bank failure (Figure 10-6). Ice jams can damage stream channels and improvements, so that the overall vulnerability to flooding is increased. Riprap can be undermined or moved out of place. Ice-jam-related damage to river training structures costs millions of dollars each year.

f. Other costs. Indirect costs associated with ice jams include loss of fish and wildlife and their habitat. Scour and erosion associated with ice jams may destroy habitat, such as eagle roosting trees, and mobilize toxic materials buried in sediment. Some scouring may, however, be beneficial to wildlife habitat as well. Shallow, vegetation-choked wetlands may be opened, allowing for fish and waterfowl spawning and brood habitat.

10-4. References

a. Required publications.

None.

b. Related publications.

Federal Emergency Management Agency 1992a
Federal Emergency Management Agency. 1992a. *Floodplain Management in the United States: An Assessment Report*, FIA-18, Boston, Massachusetts.

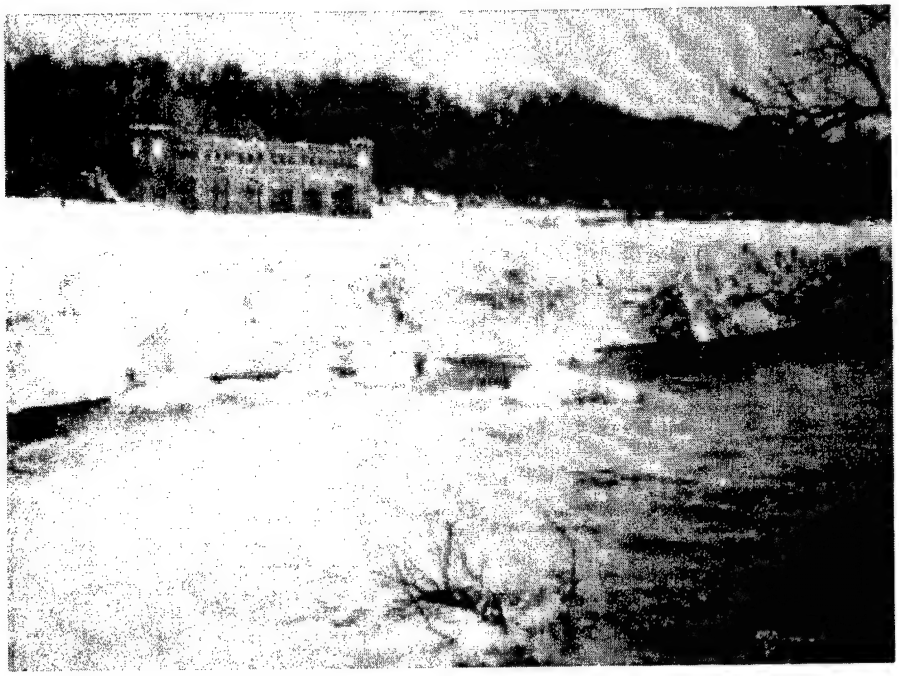

Figure 10-5. Jam immediately downstream of power plant, Fox River, near Ottawa, Illinois

Figure 10-6. Bank scour caused by a breakup jam, St. John River, near Allagash, Maine

Federal Emergency Management Agency 1992b
Federal Emergency Management Agency. 1992b. *Interagency Hazard Mitigation Team Report (Montpelier, VT)*, FEMA-938-DR-VT, Boston, Massachusetts.

U.S. Army 1980
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White, K. D. 1992. *Ice Jam Statistics Recorded on Data Base*, Ice Engineering Information Exchange Bulletin No. 2, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Chapter 11
An Ice Jam Primer

11-1. Review of Ice Types

Ice forms in freshwater bodies whenever the surface water cools to 0°C (32°F) or a fraction of a degree lower. There are many types of ice, depending on the precise mode of formation and evolution (Ashton 1986). See Chapter 2 for a thorough review.

a. Sheet ice. The ice that forms in calm water, such as lakes or reservoirs, or in slow-moving river reaches where the flow velocity is less than 0.5 m/s (1.5 ft/s), is termed sheet ice. Ice crystals formed at the water surface freeze together into skim ice that gradually thickens downward as heat is transferred from the water to the air through the ice layer. Sheet ice usually originates first along the banks and expands toward the center of the water body. In slow rivers, the sheet ice cover may also be created by the juxtaposition of incoming frazil pans generated in faster reaches upstream. Sheet ice that grows statically in place is often called black ice because of its appearance. An ice cover may also thicken at the top surface when water-soaked snow freezes to form snow ice that has a milky white appearance because of small air bubbles.

b. Frazil ice. Frazil ice (Figure 11-1) consists of small particles of ice formed in highly turbulent, supercooled water, such as river rapids or riffles, during cold, clear winter nights when the heat loss from the water to the atmosphere is very high. As the frazil particles are transported downstream, they join together to form flocs that eventually rise to the surface where they form frazil pans or floes. Frazil is often described as slush ice because of its appearance.

Figure 11-1. Frazil ice and frazil pans, Salmon River, Idaho

c. Fragmented ice. This type of ice is made up of ice pieces that originated as consolidated frazil ice pans or from the breakup of sheet ice growing at the surface of slow-moving water.

d. Brash ice. Brash ice is an accumulation of ice pieces up to about 2 meters (6 feet) in maximum dimension, resulting from the breakup of an ice cover by increasing water flow or by vessel passage. It is of particular concern in navigation channels and lock approaches.

11-2. Types of Ice Jams

An ice jam is a stationary accumulation of ice that restricts flow. Ice jams can cause considerable increases in upstream water levels, while at the same time downstream water levels may drop, exposing water intakes for power plants or municipal water supplies. Types of ice jams include freezeup jams, made primarily of frazil ice; breakup jams, made primarily of fragmented ice pieces; and combinations of both.

a. Freezeup jams. Freezeup jams are composed primarily of frazil ice, with some fragmented ice included. They occur during early winter to midwinter. The floating frazil may slow or stop because of a change in water slope from steep to mild, because it reaches an obstruction to movement such as a sheet ice cover, or because some other hydraulic occurrence slows the movement of the frazil (Figure 11-2). Jams are formed when floating frazil ice stops moving downstream, makes the characteristic "arch" across the river channel, and begins to accumulate. Freezeup jams are characterized by low air and water temperatures, fairly steady water and ice discharges, and a consolidated top layer of ice.

Figure 11-2. Frazil pans slowing down, being compressed, and breaking off in an arch shape. *The downstream movement of the pans will eventually stop. Flow is from right to left*

b. Breakup jams. Breakup jams happen during periods of thaw, generally in late winter and early spring, and are composed primarily of fragmented ice formed by the breakup of an ice cover or freezeup jam (Figure 11-3). The ice cover breakup is usually associated with a rapid increase in runoff and corresponding river discharge attributable to a significant rainfall event or snowmelt. Late season breakup is often accelerated by increased air temperatures and solar radiation.

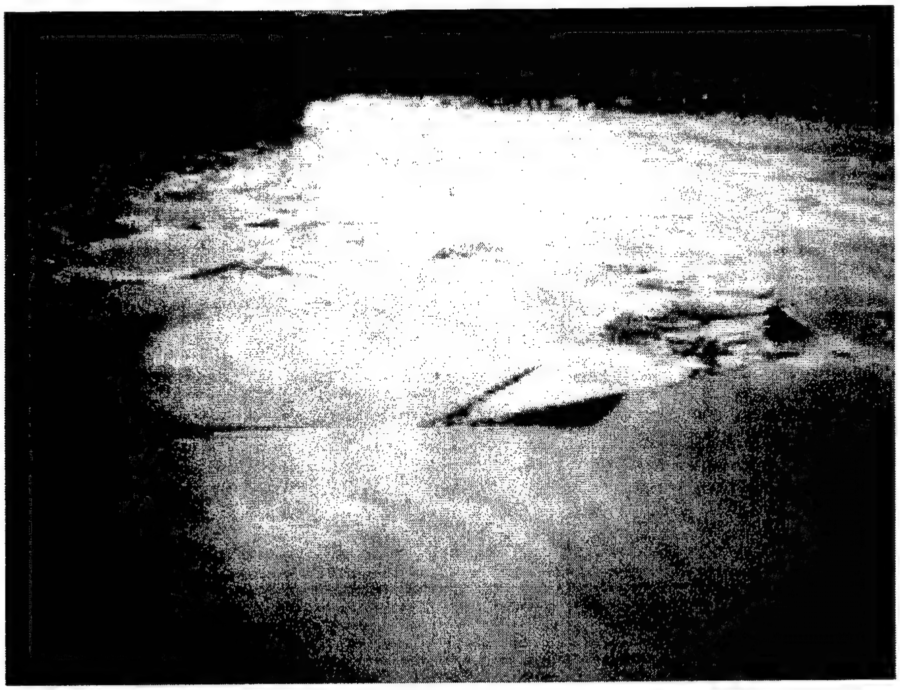


Figure 11-3. Initial breakup of sheet ice

(1) The broken, fragmented ice pieces move downstream until they encounter a strong, intact downstream ice cover, other surface obstruction to flow, or other adverse hydraulic conditions, such as a significant reduction in water-surface slope. Once they reach such a jam initiation point, the fragmented ice pieces stop moving, begin to accumulate, and form a jam (Figure 11-4). The ultimate size of the jam (i.e., its length and thickness) and the severity of the resulting flooding depend on the flow conditions, the available ice supply from the upstream reaches of the river, and the strength and size of the ice pieces.

(2) Midwinter thaw periods marked by flow increases may cause a minor breakup jam. As cold weather resumes, the river flow subsides to normal winter level and the jammed ice drops with the water level. The jam may become grounded as well as consolidated or frozen in place. During normal spring breakup, this location is likely to be the site of a severe jam.

c. Combination jams. Combination jams involve both freezeup and breakup jams. For example, a small freezeup jam forms in a location that causes no immediate damage. Before the thaw, the jam may provide a collecting point for fragmented ice that floats downstream. On the other hand, it could break up at the same time as the remainder of the river. Since the jam is usually much thicker than sheet ice, it significantly increases the volume of ice available to jam downstream.

d. Other factors. In some rivers, frazil ice does not cause freezeup jams; instead, it deposits beneath sheet ice in reaches of slow water velocities. These frazil ice deposits, called hanging dams, are

Figure 11-4. Breakup jam

many times thicker than the surrounding sheet ice growth, and will tend to break up more slowly than thinner ice. Such a frazil deposit could also provide an initiation point for a later breakup jam, as well as increase the volume of ice available to jam downstream.

11-3. Causes of Ice Jams

River geometries, weather characteristics, and floodplain land-use practices contribute to the ice jam flooding threat at a particular location. Ice jams initiate at a location in the river where the ice transport capacity or ice conveyance of the river is exceeded by the ice transported to that location by the river's flow.

a. Change in slope. The most common location for an ice jam to form is in an area where the river slope changes from relatively steep to mild. Since gravity is the driving force for an ice run, when the ice reaches the milder slope, it loses its momentum and can stall or arch across the river and initiate an ice jam. Water levels in reservoirs often affect the locations of ice jams upstream as a result of a change in water slope where reservoir water backs up into the river. Islands, sandbars, and gravel deposits often form at a change in water slope for the same reasons that ice tends to slow and stop. Because such deposits form in areas conducive to ice jamming, they are often mistakenly identified as the cause of ice jams. While these deposits may affect the river hydraulics enough to cause or exacerbate an ice jam, the presence of gravel deposits is usually an indication that the transport capacity of the river is reduced for both ice and sediment. Ice jams located near gravel deposits should be carefully studied to determine whether the gravel deposit is the cause of the jam or a symptom of the actual cause.

b. Confluences. Ice jams also commonly form where a tributary stream enters a larger river, lake, or reservoir. Smaller rivers normally respond to increased runoff more quickly than larger rivers, and their ice covers may break up sooner as a result of more rapid increases in water stage. Ice covers on smaller rivers

will typically break up and run until the broken ice reaches the strong, intact ice cover on the larger river or lake, where the slope is generally milder. The ice run stalls at the confluence, forming a jam, and backing up water and ice on the tributary stream.

c. Channel features. Natural and constructed features in a river channel may play a role in the locations of ice jams. River bends are frequently cited as ice jam instigators. While river bends may contribute to jamming by forcing the moving ice to change its direction and by causing the ice to hit the outer shoreline, water slope is often a factor in these jams as well (Wuebben and Gagnon 1995, Urroz and Ettema 1994). Obstructions to ice movement, such as closely spaced bridge or dam piers, can cause ice jams. In high runoff situations, a partially submerged bridge superstructure obstructs ice movement and may initiate a jam. In smaller rivers, trees along the bank sometimes fall across the river causing an ice jam. Removing or building a dam may cause problems. In many parts of the country, small dams that once functioned for hydropower have fallen into disrepair. Communities may remove them as part of a beautification scheme or to improve fish habitat. However, the effects of an existing dam on ice conditions should be considered before removing or substantially altering it. It is possible that the old dams control ice by delaying ice breakup or by providing storage for ice debris. Dam construction can also affect ice conditions in a river by creating a jam initiation point. On the other hand, the presence of a dam and its pool may be beneficial if frazil ice production and transport decrease as a result of ice cover growth on the pool.

d. Operational factors. Some structural or operational changes in reservoir regulation may lead to ice jams. For example, changes in hydropower operations can inadvertently cause ice jam flooding. Sudden releases of water, such as those characteristic of peaking plants, may initiate ice breakup and subsequent jamming. On the other hand, careful reservoir regulation during freezeup or breakup periods can reduce ice jam flood risks.

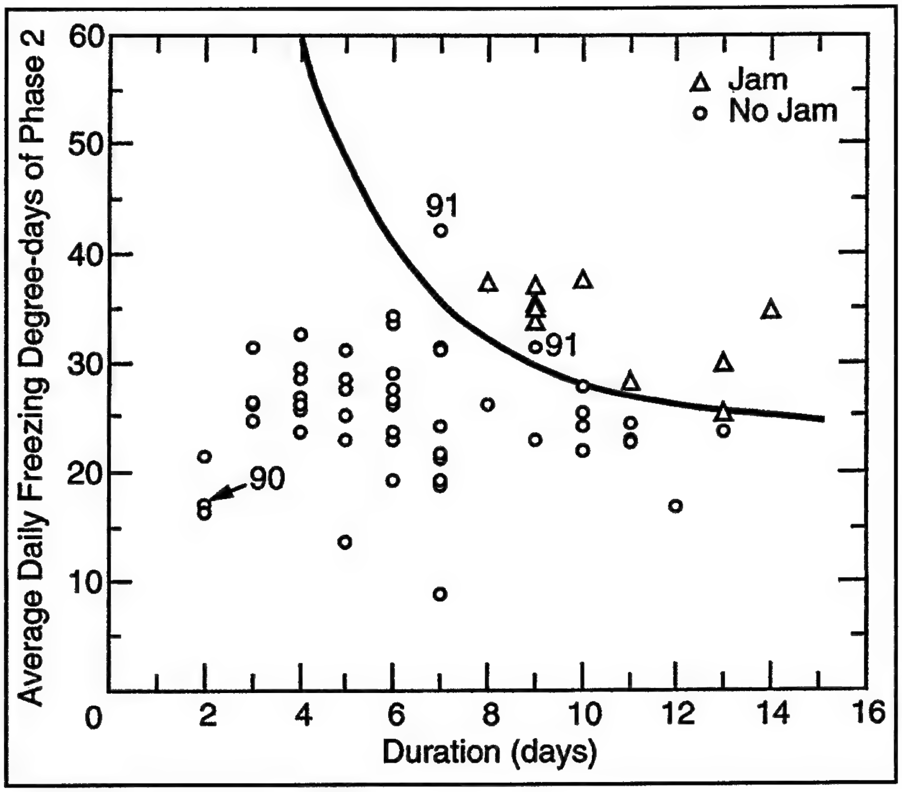
11-4. Predicting Ice Jams

Very few methods for predicting ice jams exist, and those that do are highly site-specific, requiring knowledge of the location of the jam initiation point. Because freezeup jams rely heavily on periods of intense cold that produce large quantities of frazil, they can be somewhat easier to predict than breakup jams, which are caused by a site-specific combination of complex physical processes. Evaluation of historical ice, meteorological, and hydrological records is necessary for developing a prediction method for either type of jam. For example, Zufelt and Bilello (1992) used historical records, along with river geometry, to develop a method to predict the progression of freezeup jams in Idaho. Their model results showed that ice jam flooding at that location could be related to the accumulated freezing degree-days and the duration of periods of extreme cold (Figure 11-5). Wuebben and Gagnon (1995) ranked meteorological and hydraulic parameters for known jam and no-jam events in North Dakota to determine the likelihood of breakup jam flooding, with good results. They selected model parameters after studying the physical processes at the site, and all relate to the stage and ice thickness the time of breakup. Table 11-1 presents the parameters and their assigned weighting factors.

11-5. References

a. Required publications.
None.

b. Related publications.



a.

Figure 11-5. Example freezeup prediction model for Salmon River, Idaho. *The curves apply to antecedent periods (Phase I) of less than 500 (Fahrenheit) or 278 (Celsius) AFDD (left) and more than 500 (Fahrenheit) or 278 (Celsius) AFDD (right)*

Ashton 1986
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Urroz, G.E., and R. Ettema. 1994. "Application of Two-Layer Hypothesis to Fully Developed Flow in Ice-Covered Curved Channels," *Canadian Journal of Civil Engineering*, Vol. 21, no. 1, pp. 101-110.

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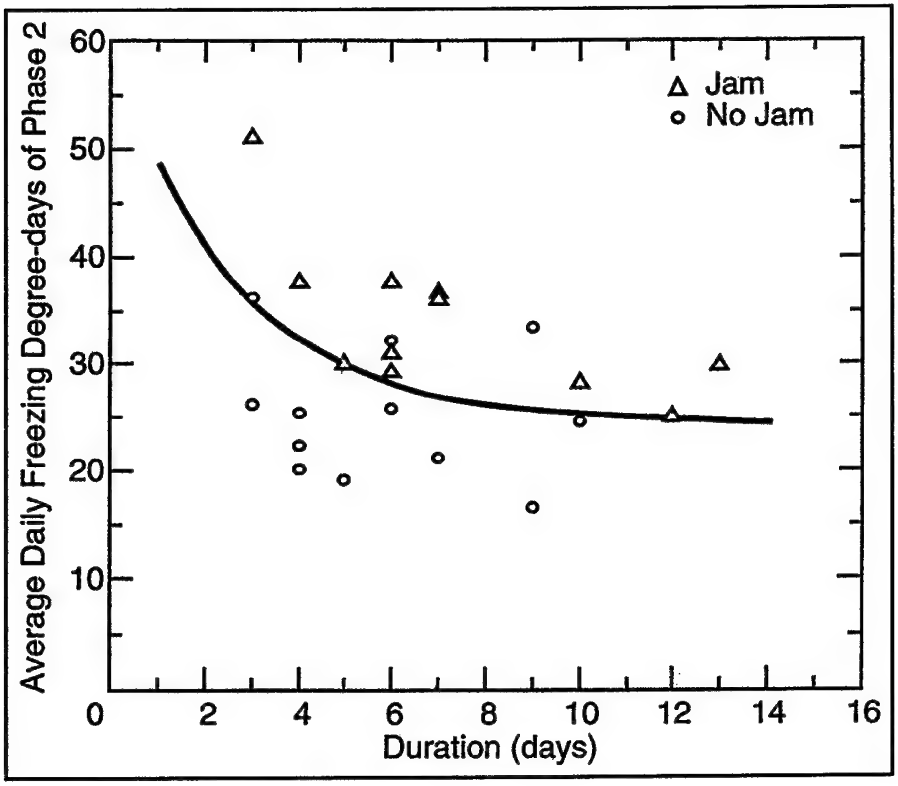
Wuebben, J.L., and J.J. Gagnon. 1995. *Ice Jam Flooding on the Missouri River near Williston, North Dakota,* CRREL Report 95-19, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Zufelt and Bilello 1992
Zufelt, J.E., and M.A. Bilello. 1992. *Effects of Severe Freezing Periods and Discharge on the Formation of Ice Jams at Salmon, Idaho,* CRREL Report 92-14, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.



b.

Figure 11-5. (Concluded)

Table 11-1
Upper and Lower Threshold Limits and Weighting Factors in Wuebben's Complex Threshold Model for Prediction of Ice Jams at Williston, North Dakota

Parameter	Lower Threshold	Upper Threshold	Weight
ΣFDD_{max}, °F days (°C days)	1700 (944)	2600 (1444)	2
Q_{max}, ft^3/s (m^3/s)	< 25000 or > 86800 (<708 or > 2458)	30000 < xi < 70000 (850, xi < 1982)	1
Julian day of ΣFDD_{max}	150	165	1
Julian day of Q_{max}	155	170	1
Julian day of ΣFDD_{max} - Julian day of Q_{max}	<-8 or > 10	-5 < xi < 7	2
Lake Sakakawea stage, ft MSL (m MSL)	1835 (559.3)	1840 (560.8)	1
Total snowfall, in (cm)	20 (50.8)	40 (101.6)	2
Timing of snowfall, in (cm)	< 5 (12.7) after JD = 90	> 10 (25.4) after JD = 90 or > 5 (12.7) after JD = 120	1 1

Chapter 12
Ice Jam Mitigation Techniques

12-1. Ice Jam Flood Control

a. General. Until the 1970s, flood control concentrated largely on open-water flood events and was considered primarily a Federal responsibility. Large structural solutions such as levees or flood-control dams were built. Now, the Federal Government requires local and State governments to share the costs, and Government policies favor small-scale, locally funded projects. In light of significantly reduced budgets, innovative ice jam mitigation techniques that require low maintenance and low up-front costs, have low environmental impacts, and yield excellent results in terms of reduced flooding damages are being developed. Many of these are appropriate for design and implementation in smaller cities and towns.

b. Effects of flood insurance. In 1990 the Federal Emergency Management Agency (FEMA) initiated the Community Rating System to reward local hazard mitigation efforts by reducing flood insurance premiums in communities that adopt relocation, hazard area acquisition, and other mitigation policies. "Clearly, Federal flood hazard policy is demonstrating an increasing emphasis on mitigation. Mitigation works to change the nature of the threat, decreases vulnerability to damage and reduces exposure to the hazard" (Drabek and Hoetmer 1991).

12-2. Types of Mitigation Measures

A number of ice jam flood mitigation measures are possible. These measures can be of a structural or non-structural nature, appropriate to control breakup jams or freezeup jams. Some are permanent, some are deployed in advance of an anticipated flood threat, while others are deployed under emergency conditions when a jam has formed and flooding has occurred.

a. Structural measures. Structural measures for ice jam control may incorporate features that can be used to alleviate open-water flooding, as well as those designed specifically for ice jam floods. The cost of such measures includes construction, operation, and land acquisition, as well as costs associated with recreation and environmental mitigation. Unfortunately, while they are often very successful, structural solutions tend to be expensive. Structural solutions remain appropriate on rivers where chronic or serious threats persist, and where the extent of potential damages justifies the cost. Although the majority of the structural mitigation techniques are, by their very nature, permanent, some are designed to be removable. These removable structures are usually installed at the beginning of winter and removed after spring breakup when the threat of ice jam flooding no longer exists. A few removable structures are designed to be deployed after an ice jam threat has been identified and, in this respect, can be considered advance mitigation measures.

b. Nonstructural measures. These measures are designed to modify vulnerability to the flood threat or to reduce the severity of the ice jam and of the resulting flood. They are generally less expensive than structural solutions. The majority of the nonstructural techniques are used for advance and emergency measures when serious ice jam flooding is imminent or under way. For example, if sufficient warning is provided, ice can be weakened (by cutting or dusting) before an ice jam takes place. Blasting and mechanical removal are often employed only as emergency mitigation measures once ice jams have happened. The creation of ice storage zones upstream from a known jam site to minimize the amount of ice

reaching the jam site is a permanent measure, since these areas, once established and properly maintained, can be used year after year.

c. Freezeup jam mitigation. Freezeup ice jam control usually targets the production and transport of the frazil ice that causes jams. This may be accomplished by encouraging the growth of an ice cover that insulates the water beneath, decreasing the production of frazil ice. The ice cover collects and incorporates frazil ice that is transported from upstream. This reduces the amount of ice moving downstream.

d. Breakup jam mitigation. Breakup ice jam control focuses on affecting the timing of the ice cover breakup, thereby reducing the severity of the resulting jam to the point where there is little or no flooding. Breakup mitigation may also aim at controlling the location of the ice jam by forcing the jam to occur in an area where flooding damages will be inconsequential.

12-3. Selecting Mitigation Measures

Table 12-1 summarizes the currently available jam mitigation techniques and indicates whether they are applicable to freezeup or breakup jams and whether they are appropriate for permanent, advance, or emergency measures. In paragraph 12-4 and those following, the ice jam mitigation methods are described in detail: first, those that are primarily permanent measures; second, those appropriate for advance measures; and third, those applicable to emergency situations. Traditional flood-fighting methods, namely floodproofing, sandbagging, levee closing, or evacuation, are obviously applicable to ice jam floods. They are only briefly summarized under the pertinent subparagraphs.

a. Mitigation strategy. The best mitigation strategy often combines structural and nonstructural measures, such as an ice boom associated with temporary modifications in the operation of an upstream water control dam, as well as permanent, advance, or emergency measures. Table 12-2 lists common ice jam mitigation strategies and corresponding techniques.

b. Data collection. Following an ice jam flood, when an ice jam control program is developed to prevent similar events from recurring, it is first necessary to determine the type of jam, source of ice, local and remote causes of the jam, and meteorological and hydrological conditions that led to the jam formation. To address all of these points, an ice jam data collection program, as described by White and Zufelt (1994) or Elhadi and Lockhart (1989), should be an integral part of an ice jam mitigation effort. Data collection should not be limited to the immediate vicinity of the jam location. It is important to study upstream and downstream areas, since the source of ice and the actual causes of ice jamming at a particular site may be far removed from the actual jam location. This data-gathering phase of the program is critical to selecting the jam mitigation strategy and corresponding mitigation techniques best appropriate to the site under study.

c. Coordination. Successful ice jam mitigation often requires multi-jurisdictional cooperation and interagency coordination. For example, a catastrophic breakup ice jam on the Delaware River in February 1981 affected three states and caused $14.5 million in damages. After extensive collaboration among Federal and State agencies in New Jersey, Pennsylvania, and New York, a diversion channel was proposed to be built physically in New Jersey that also provided major flood loss reduction benefits to New York and Pennsylvania.

Table 12-1
Ice Jam Mitigation Methods

Technique	*Jam Type*	*Type of Mitigation*
Structural		
Dikes, levees, floodwalls	F,B	P
Dams and weirs	F, B	P
Ice booms	F, B	P, A
Retention structures	B	P
Channel modifications	F, B	P
Ice storage zones	B	P, A
Nonstructural		
Forecasting	F, B	A, P
Monitoring and detection	F, B	E, A, P
Thermal control	F, B	E, A, P
Land management	F, B	P
Ice cutting	B	A
Operational procedures	F, B	A, P
Dusting	F, B	E, A
Ice breaking	F, B	E, A
Mechanical removal	F, B	E, A
Blasting	F, B	E, A
Traditional Techniques		
Floodproofing	F, B	P
Sandbagging	F, B	A, E
Evacuation	F, B	A, E
Levee closing	F, B	A, E
Key:	B = Breakup jam F = Freezeup jam	P = Permanent measure A = Advance measure E = Emergency measure

12-4. Permanent Measures

In this paragraph, several measures are briefly discussed that can be considered for the permanent or long-term correction of ice jamming problems. See Part I, Chapter 3, *Ice Control*, for greater detail and description of certain of these measures.

a. Dikes, levees, and floodwalls. Dikes, levees, and floodwalls physically separate the river from property to be protected. These measures protect against open-water floods as well as ice jam floods. However, designs adequate for open-water protection may not be adequate to handle ice jam stages that cause physical damage.

Table 12-2
Ice Jam Mitigation Strategies and Applicable Techniques

Protect surrounding areas from flood damages
Dikes, levees, and floodwalls
Floodproofing
Floodplain land-use management
Sandbagging
Levee closing
Evacuation
Reduce ice supply
Thermal control
Revised operational procedures
Ice booms
Dams and weirs
Ice storage zones
Dusting
Ice retention
Increase river ice and water conveyance
Channel modifications
Revised operational procedures
Control ice breakup sequence
Detection and prediction
Ice booms
Ice cutting
Ice breaking
Revised operational procedures
Displace ice dam initiation location
Dams and weirs
Ice piers, boulders, and cribs
Ice booms
Ice breaking
Channel modifications
Remove ice
Thermal control
Ice breaking
Mechanical removal
Blasting

b. Dams and weirs. Dams are used to affect the thermal and flow regimes of a river. As breakup jam control structures, dams are designed to suppress or change the duration or timing of ice jam formation downstream by intercepting the solid ice pieces coming from upstream. For freezeup jam control, a dam promotes the formation of an upstream stable sheet-ice cover to minimize the generation of frazil ice that could result in the formation of a freezeup jam. For example, gates may be designed to allow run-of-river flow during most of the year, but in the winter be closed at freezeup so rapids are inundated (Figure 12-1). This eliminates local frazil ice production, reduces the supply of frazil moving downstream, and slows the freezeup jam progression.

(1) A dam designed to reduce ice jam flooding can be part of a multi-objective community project, where benefits for open-water flood control, navigation, recreation, water supply, irrigation, or hydropower justify much of the construction costs.

(2) For smaller rivers, when financial or environmental constraints eliminate consideration of major structural works, relatively low-cost alternatives can still provide significant ice jam control. For freezeup control, a still experimental fabric tension weir (Figure 12-2), supported by cables anchored at the banks, may be an economically feasible alternative. For breakup control, a permeable,

Figure 12-1. Lancaster, New Hampshire, ice-control structure

Figure 12-2. Tension weir

cable-supported wire mesh, similar to submarine net (Figure 12-3), may be strung across the stream to temporarily hold ice from upstream while the downstream reaches of the stream are cleared of ice. These two types of structures are removable and can be seasonally deployed. However, they often require local bed and bank protection against scour for stability and effectiveness. Provisions to allow part of the flow to divert around the structures to limit the upstream flow depth may be required.

c. Ice booms. Ice booms are the most widely used type of ice-control structure (Figure 12-4). They are a series of timbers or pontoons tethered together and strung across a river to control the movement of ice. Booms are flexible and can be designed to release ice gradually and partially when overloaded. Ice booms are relatively inexpensive and can be placed seasonally to reduce negative environmental impacts.

(1) Booms commonly stabilize or retain an ice cover in areas where surface flow velocities are 0.69 m/s (2.25 ft/s) or less and relatively steady. In some cases, a weir or small structure can improve hydraulic conditions at the ice boom location, especially on small, steep streams. Some booms are located at the outlets of lakes or reservoirs to keep ice from entering downstream ice-jam-prone reaches.

(2) Conventional ice booms may be used in breakup situations to hold back the ice for a brief time, allowing the initiation of emergency response measures, such as evacuation or sandbagging. Booms can be placed to direct the movement of ice pieces away from an intake or navigation channel. Ice-control booms are also used to promote ice cover formation during freezeup as part of freezeup ice jam mitigation efforts.

d. Ice retention. Ice retention structures control breakup jams by promoting the initiation of an ice jam at a suitable location where flooding will cause little or no damage. Fragmented ice is captured and retained upstream from the retention structure to create the ice jam. Ice retention structures can range from suspended structures, such as a submarine net or vertically oriented ice booms, to streambed structures, such as concrete piers (Figure 12-5), large boulders, or rock-filled cribs placed at regular intervals across the width of the stream. Provision for a floodplain or diversion channel may also be required to limit the rise in upstream water levels and the corresponding loads on the structural elements, as well as to limit the upstream flooding potential.

(1) Suspended structures may be placed seasonally but require adequate permanent anchoring to withstand the ice forces. These structures are generally more suited to smaller rivers and streams. The size and anchoring of projecting structures, such as piers, boulders, or cribs, must be determined to withstand the anticipated ice forces, and their spacing is a function of the average ice floe size.

(2) Retention structures for ice jam control do not block the entire river width, and thus allow for recreational navigation and fish passage. Therefore, they can be installed permanently. The bed of the stream may need to be protected against scour around all elements of this type of structure to ensure that they remain stable.

e. Channel modification. Modifications to the river channel can improve the passage of ice through reaches where ice jams tend to form, such as changes in slope, river bends, slow moving pools, and constrictions. Dredging or excavation can widen, deepen, or straighten the natural channel. Old bridge piers and natural islands and gravel bars can be removed. Diversions (Figure 12-6) can bypass ice and water flow around the normal jamming sites, lowering the upstream stage. When diversion channels are used, they should be designed to remain dry except during floods, so that they will be available to function as open-water channels and not contribute to the downstream ice supply. A diversion channel can improve the performance of an ice-control structure. If an ice-control dam or weir is used to control a

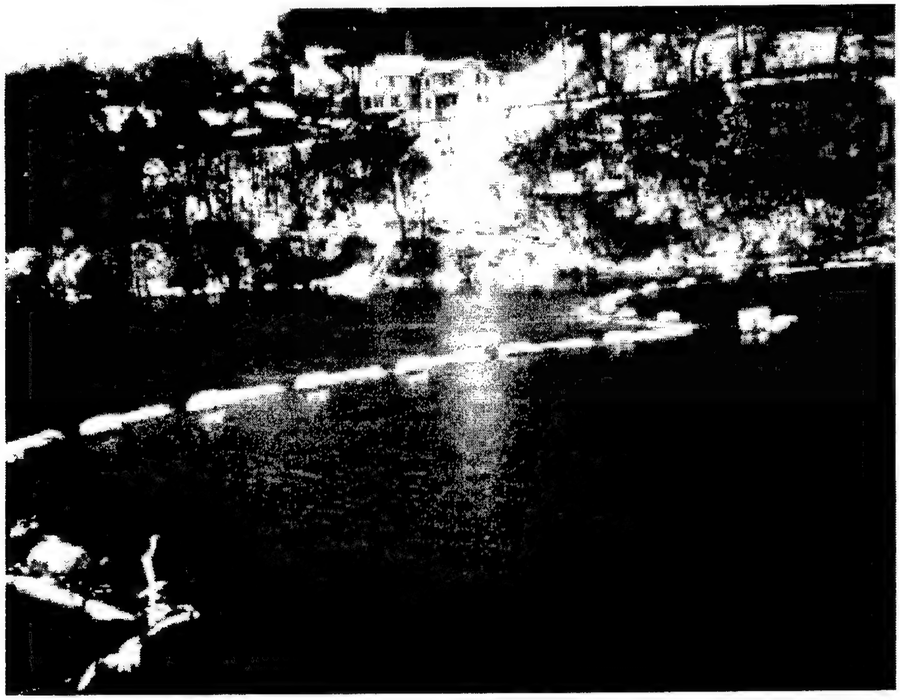
Figure 12-3. Submarine net

breakup ice run, an associated high-level diversion could be used to limit the discharge reaching the structure, reducing river stages to prevent local flooding, and ensuring the stability of the ice being retained.

f. Creation of ice storage zones. Breakup ice jam frequency and flood levels can be reduced through storage of ice upstream from damage-prone areas in ice storage zone sites (Figure 12-7). Ice storage zones reduce the volume or rate, or both, of ice moving to a downstream jam location. By developing low overbank areas, where ice can easily leave the channel during breakup, perhaps supplemented by dikes or booms to redirect ice movement, the volume of ice passing downstream can be substantially reduced. The ice left behind settles in side channels, the floodplain, or on the riverbanks. Another approach is designing and creating ice storage zones to *enhance* natural jamming. Measures such as minor channelization, tree removal, bank regrading, berm construction, and installation of booms, piers, or other in-stream structures can be employed to initiate an ice jam at a location where ice storage will be maximized, damage will be minimal, and potential for failure and release of the jammed ice is low.

g. Thermal control. Thermal control of ice jams uses an existing source of warm water to melt or thin a downstream ice cover. Water, even a fraction of a degree above freezing, can be quite effective in melting ice over a period of days or weeks (Wuebben and Gagnon 1995).

(1) External heat sources include cooling water discharges from thermal power plants, wastewater treatment plant effluent, and groundwater. The thermal reserve provided by water in nearby lakes and large reservoirs may also be a source of warm water for thermal control. Because water reaches its maximum density at a temperature of about 4°C (39°F), colder water in lakes tends to stratify above warmer water. An ice cover can form on the water surface, even though the water at depth is still well



a. Prior to freezeup

b. After freezup

Figure 12-4. Ice boom on Allegenhy River near Oil City, Pennsylvania

Figure 12-5. Ice piers for breakup control

above freezing. Warm water can be brought to the surface using air bubblers, pumps, or flow enhancers. In the case of a reservoir, a low-level outlet in a dam may be used to release warm water.

(2) Warm water inputs can thin an ice cover prior to breakup, so that it will not provide a jam initiation point. Warm water inputs can also reduce the volume of ice available to jam. Thermal control may be used to melt or thin an existing ice jam, thereby increasing the flow area within the jam and decreasing upstream water levels.

h. Floodplain land-use management and mapping. The best strategy for reducing flood losses is to keep people and property out of the floodplains. Appropriate land-use planning would dramatically reduce the flood damage potential. This is particularly applicable in areas that experience chronic flooding. Floodplain mapping is essential for careful land-use decision making. More than 20,000 communities have floodplain maps prepared by the National Flood Insurance Program. Since most flood insurance studies were prepared for open-water flood events, ice jam flooding may not conform exactly to the regulatory or mapped floodplains. However, these maps remain useful tools for determining general floodplain boundaries and elevations.

i. Floodproofing. There are four basic types of floodproofing to minimize damage to individual structures during floods (Figure 12-8). These are: 1) raising or relocating of a building, 2) barrier construction, 3) dry floodproofing, and 4) wet floodproofing. Specific techniques of floodproofing are presented in the Corps manual on floodproofing (U.S. Army 1991).

(1) Raising a building usually involves jacking it up and setting it on a new, higher foundation, so that the inhabited areas and utilities are above predicted flood levels. Care must be taken that the new foundation can withstand the expected forces from the water flow and ice and debris loading. Sometimes

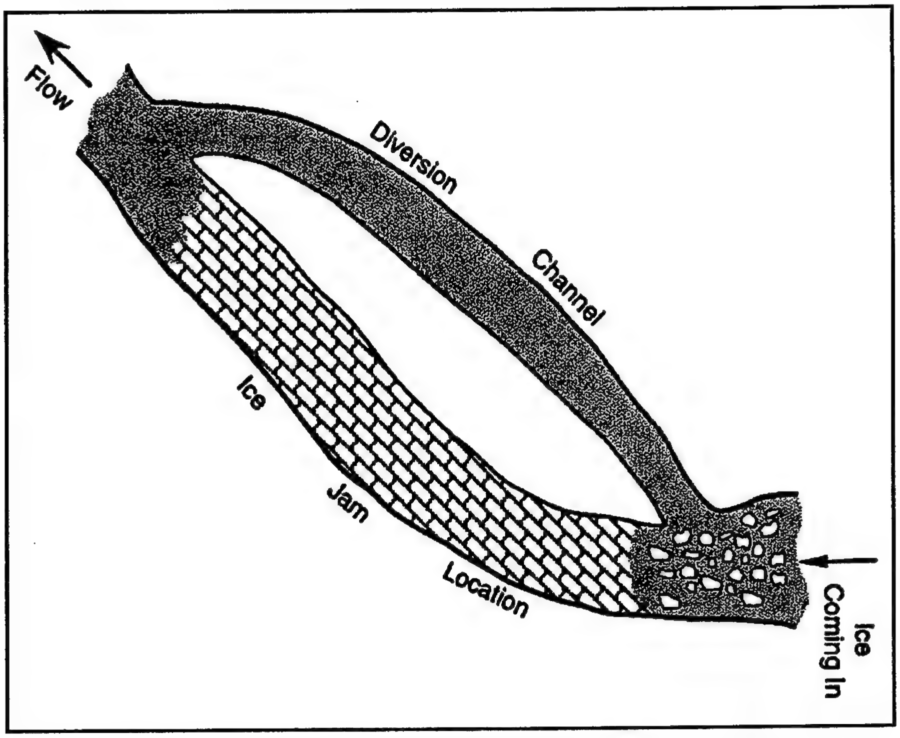


Figure 12-6. Schematic of diversion channel for ice jam flooding control

this requires openings to allow flow through the new foundation. Relocation of the building to higher ground is quite effective but not always possible or acceptable.

(2) While raising or relocating buildings are very effective methods of floodproofing, barrier construction can be equally effective in some cases. Barriers such as berms or floodwalls are constructed around a building to prevent floodwaters from reaching it. Openings in the barrier (for example, a driveway) should be avoided. Possible sources of flow through the barrier, such as seepage through the barrier and inflow from water or sewage lines, must be considered in barrier design.

(3) Dry floodproofing involves sealing the outside of the building to prevent floodwaters from entering. Dry floodproofing is usually only considered for cases where flood levels are less than a few feet above the base of the building, because at higher levels the pressure of the water (and ice) can collapse walls.

(4) Wet floodproofing allows the flood waters to enter a structure while at the same time minimizing damage by relocating utilities, such as furnaces or hot water heaters, above predicted high water levels. Wet floodproofing can be used where construction of barriers and dry floodproofing are not feasible.

12-5. Advance Measures

Mitigation measures deployed in anticipation of actual ice jam flooding are known as advance measures. These measures are used to reduce vulnerability to ice-jam-related flooding. Some emergency measures, such as ice removal, may also be initiated in advance of flooding.

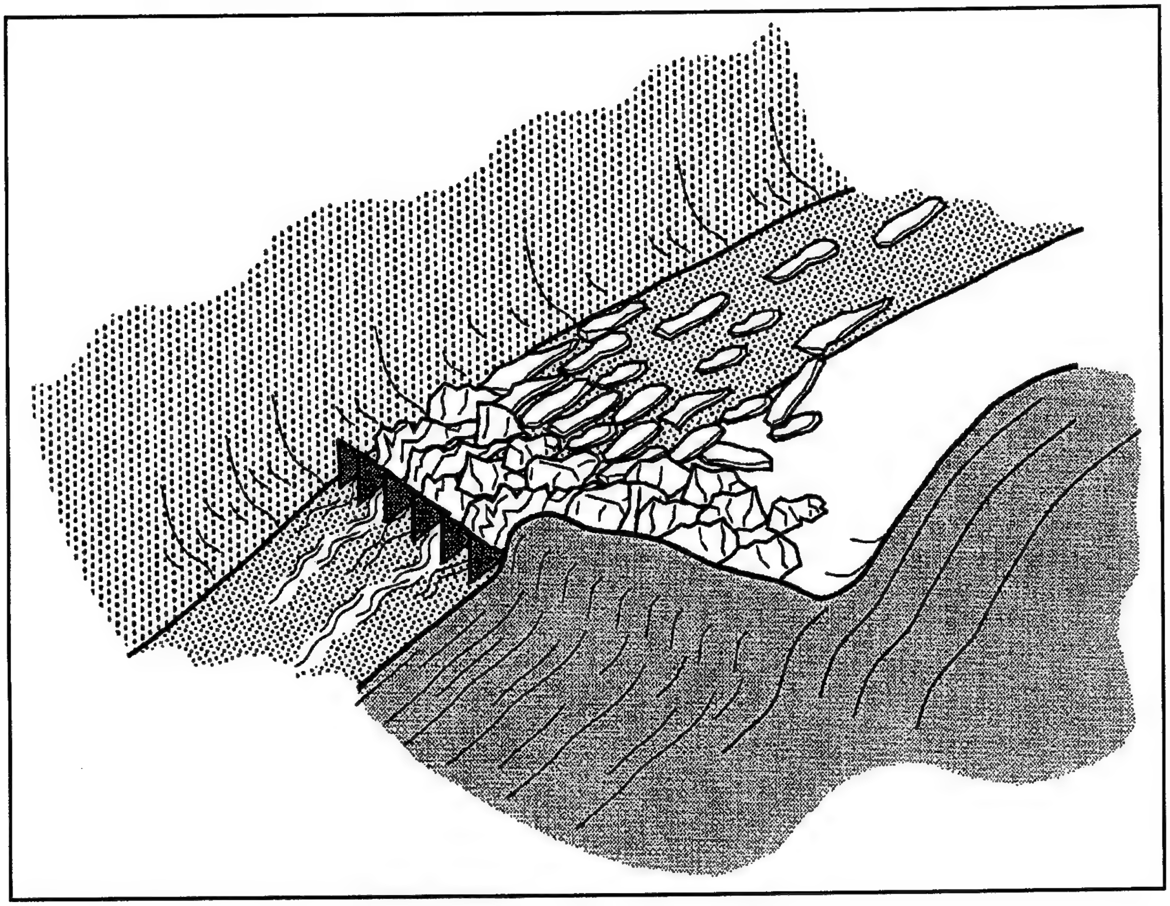


Figure 12-7. Ice storage zone combined with ice retention structure

a. Forecasting. Because of the highly site-specific nature of ice jams, limited available data on ice jams, and the complexity of the hydrological, meteorological, and hydraulic processes involved in the formation of ice jams, forecasting ice jam flooding on a general level is not yet feasible. However, it is possible to analyze various ice jam parameters and develop a range of values that can be used to estimate the likelihood of a particular ice jam occurring under certain conditions (Wuebben et al. 1992). As more communities adopt flood detection systems, forecasting potential to reduce losses improves. Refer to Chapter 11, paragraph 11-4, for additional discussion of ice jam forecasting.

b. Monitoring and detection. The effects of ice jam flooding are often more localized than those of open-water floods. Therefore, it is difficult to generalize ice jam data regionally. Since analytical techniques are less developed than those for open water floods, there is a stronger need for local historical data to serve as the basis for policy making. Simple remote gages to collect data on river ice movement and breakup are useful. Water level gages can detect any rapid increase in river stage, which often precedes ice breakup. Automated temperature sensors help to verify whether conditions are conducive to ice jam formation or breakup. Ice motion detectors (Zufelt 1993) can be imbedded in intact ice covers prior to breakup to give advance warning of the initiation of breakup upstream from a likely jam site (Figure 12-9). Existing gages can be augmented with telemetry transmitters that send data directly to a local monitoring center or State and Federal agencies (e.g., National Weather Service or U.S. Geological

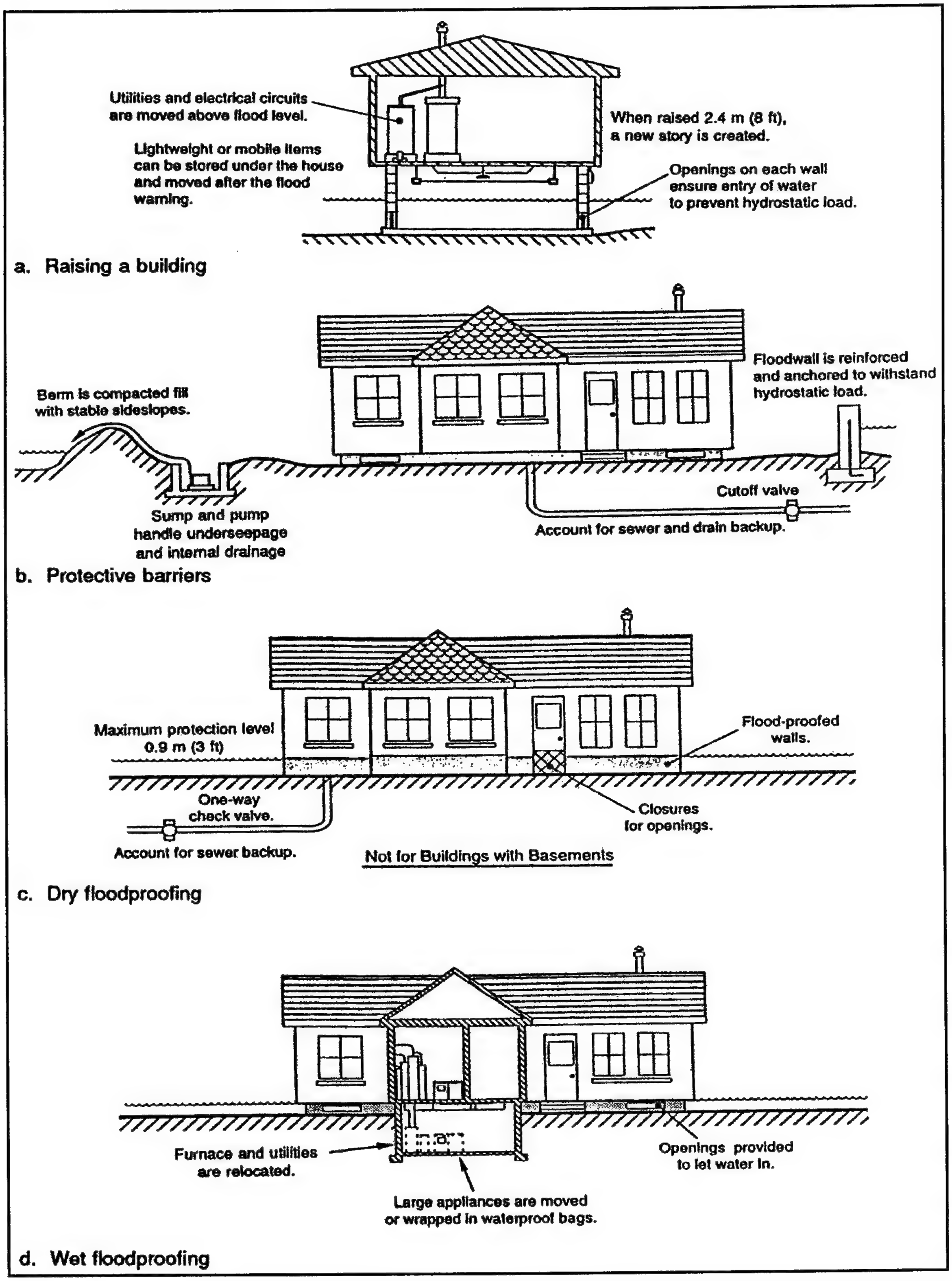


Figure 12-8. Floodproofing techniques (U.S. Army 1991)

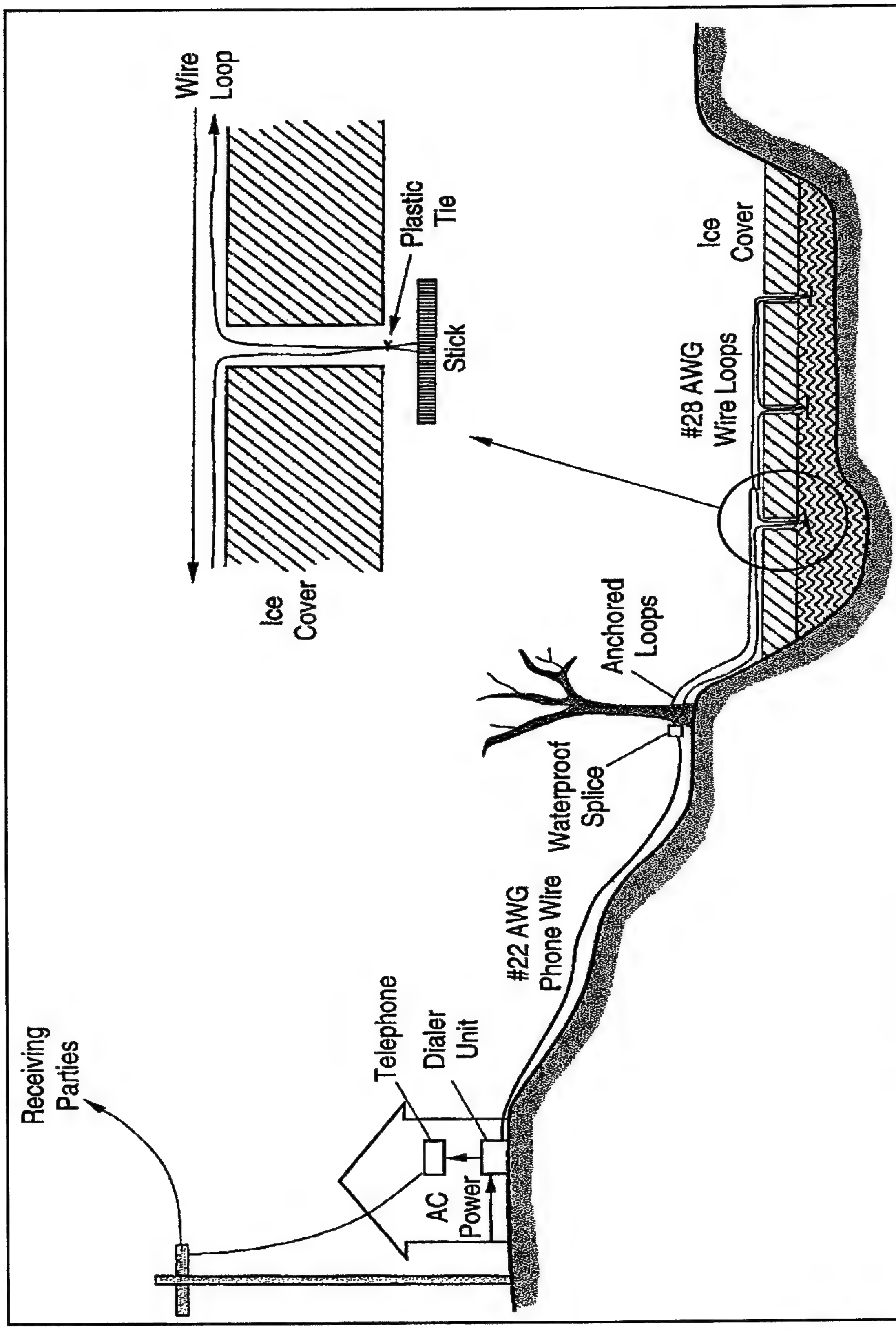


Figure 12-9. Schematic of ice motion detectors

Survey) by telephone, radio, or satellite. An effective warning system must include a fully developed response system, in addition to a detection system, to save lives and reduce property damages.

c. Ice cutting. Mechanical or thermal ice cutting creates areas of weakness in an ice cover. This technique may be used to cause a stable ice sheet to break up earlier than normal, preventing it from acting as an obstruction to movement of upstream ice. On the other hand, ice cutting in selected locations can create a flow path for ice and water at breakup, reducing the probability of jamming. Ice cutting (Figure 12-10) involves carving trenches in the ice, either mechanically (using a chainsaw, a trenching machine, a backhoe, or some other convenient device) or thermally (using a source of warm water or a substance that reacts chemically with the ice and melts it). The trenches can be partial or the full depth of the ice. They may follow the natural thalweg of the river channel, be cut along the edges of the channel to facilitate movement of the ice sheet, or be cut in a pattern designed to weaken the ice sheet. Ice cutting must be carefully timed to avoid refreezing the slots.

d. Revised operational procedures. Flow control may be available at dams or navigation structures located upstream or downstream from an ice jam problem site. The pool level can be raised or lowered to change the location of jamming in the river above the pool. Lowering the pool level early in the winter may expose some frazil ice production areas that would otherwise be covered. Lowering the pool after an ice cover has formed allows additional runoff storage before breakup. Discharge can be lowered at critical periods during ice formation to lower velocities and induce rapid and more extensive ice cover formation downstream. At breakup, lower discharge can decrease ice jam flooding or, in some cases, eliminate ice jam formation.

e. Dusting. By dust is meant any dark substance that can be spread on the ice in a thin layer to absorb solar radiation and thereby alleviate possible jam conditions before the fact. Covering ice surfaces with a thin layer of dark material induces more rapid melting and ice weakening (Figure 12-11). Conventional materials include coal dust, fly ash, top soil, sand, and riverbed material. Initial tests with biodegradable materials, such as leaves, mulch, and bark, show promising results (Haehnel et al. 1996). These types of materials are more easily spread than sand or coal dust by means of commercially available seeders and spreaders, but the materials must be dry enough to flow freely for even distribution and to avoid freezing. The rough surface of an actual jam creates so many shadows that dusting is generally not effective. Wind can be a problem, causing the finer dusting materials to drift or snow to drift over the dust (Moor and Watson 1971). Moor and Watson describe a reach of the Yukon River downstream of Galena, Alaska, which has regularly caused ice jams. Dusting this reach each spring, 2 to 3 weeks before breakup, weakens the ice sufficiently that the frequency of jams is much less there since the practice started. Ideally, the dust should be applied as early as possible but after the last snowfall.

(1) In general, the ice could be weakened by dusting in any reach where the cover regularly stops the ice run and causes a jam. The degree of melting depends on the quantity and material properties of the material deposited, solar radiation, and snowstorms. In areas where there are late snowstorms, several applications may be necessary. The melting period may be too short for significant reduction in ice volume or weakening if breakup takes place rapidly. The possible adverse environmental impacts of dusting materials must be considered before they are applied.

(2) The dusting operation should spread the material layer as evenly as possible. A surface concentration of about 50 percent should be the goal; too much dusting material insulates the ice rather than acting to promote deterioration. Important factors are time, the higher sun angles in the late spring, and good luck in avoiding snowstorms that would cover the dust. Agricultural aircraft generally apply

Figure 12-10. Ice cutting

the dust, which keeps costs fairly low. Moor and Watson (1971) give a cost of 34.9 cents (1970 dollars) per lineal foot (100 feet wide) ($1.14 per lineal meter [30.5 meters wide]) in a remote section of Alaska. White and Kay (1997) give 31.7 cents (1994 dollars) per lineal foot (30 feet wide) ($1.04 per lineal meter [9.1 meters wide]) for dusting on the Platte River, Nebraska.

(3) The particle size can vary, depending on what is available. Moor and Watson (1971) quote 0.5 pounds per square yard (0.27 kg/m^2) for sand and 0.35 pounds per square yard (0.19 kg/m^2) for fly ash. V.I. Sinotin (1973) gives similar rates: for 0.04-inch (10-millimeter) diameter dust he suggests 0.18 pounds per square yard (0.10 kg/m^2) and for 0.2-inch (51- millimeter) dust, 0.92 pounds per square yard (0.50 kg/m^2).

(4) A logical offshoot of dusting is to pump water and bottom materials onto the ice surface. This is limited to streams with silt or sand bottoms and, according to Moor and Watson (1971), is ten times more expensive than aerial dusting. However, the approach does have application where the stream is too narrow or sinuous for aerial work, or where environmental considerations preclude adding material to the stream.

12-6. Emergency Management for Ice Jam Flooding

Emergency measures are those taken after an ice jam has formed and flooding is imminent or already happening. The effectiveness of the emergency response may be reduced unless an emergency action plan exists that specifically refers to ice jams. Comprehensive emergency management includes four phases: preparedness, response, recovery, and mitigation. See *Natural Disaster Procedures*,

Figure 12-11. Ice dusting

ER 500-1-1, for additional information and guidance. Emergency planners should have a clear line of command for multi-governmental management of ice jam flooding events. Plans should be tested in advance to be sure that all phases can be carried out and that all necessary materials and equipment are available when needed. Before implementing emergency measures, it is necessary to monitor the river ice conditions upstream as well as downstream from the jam site so as to select the best measures and to eliminate those that may only displace the flooding problem to another location. Early ice monitoring can also provide lead time to allow other emergency measures to be taken. For example, the jam progression rate is important in freezeup ice jams, particularly when severe cold conditions conducive to rapid progression are forecast. For breakup jams, knowledge of the upstream ice thickness, extent, and relative strength is needed in estimating the remaining ice supply to the jam. The downstream ice conditions also need to be assessed, if only to determine whether or not there is sufficient open-water area to receive ice when the jam releases.

12-7. Emergency Measures

Ice jam emergency response measures include the specific measures of ice breaking, mechanical ice removal, and ice blasting, plus the traditional flood fighting efforts of evacuation, levee closing, and sandbagging, all of which qualify as advance measures.

a. Icebreaking. This technique is only usable in a few rivers. Ice covers can be broken prior to natural breakup using icebreaking vessels or construction equipment (Figure 12-12). Downstream movement of the broken ice should be enhanced to prevent localized breakup ice jams. Icebreaking is particularly useful to ease navigation in larger rivers and lakes. See Chapter 17 for a more comprehensive discussion of icebreaking.

Figure 12-12. Icebreaking vessel

(1) When the channel depth is sufficient and the ships are available, icebreakers are certainly the easiest, safest, and possibly the cheapest way to break up a jam. This operation is carried out by the captains, who are responsible for the safety of their ships, so little more needs to be said regarding safe operations. However, icebreaker operation can be expensive, and icebreakers cannot be used in small rivers of limited depth. The availability of an icebreaker on short notice and the difficulty of access to the ice in upstream reaches can also limit this method.

(2) Reinforced lake tugs and river icebreakers are used to clear harbors and rivers, primarily in the Great Lakes system. On large rivers open to commercial navigation, towboats are used to break a channel through level ice or localized ice accumulations. The most powerful towboats available are needed for this purpose. Ideally, two or more towboats work *en echelon* (staggered, one behind and to the side of the other), with the largest or more powerful towboat in the lead. The following ship has to be careful to ensure an equal width channel. If it crosses the path of the leader, the resulting narrow section will inevitably cause a jam and the downstream channel will no longer keep itself clear.

(3) Occasionally, if circumstances permit, an icebreaking vessel can work in conjunction with blasting (discussed below). The propeller wash and wave action of the ship will help to quickly clear the ice loosened by the blasting, and the ship will offer a factor of safety for the people on the ice. A combined operation like this will require extra cooperation as well as good communication.

(4) When a river ice jam is very thick, two towboats of essentially equal power have been used together. They mate-up bow to bow, and while the propeller wash of one boat loosens and erodes the ice, the second boat holds the first in position. This operation takes a great deal of skill and coordination between the pilots.

(5) Air cushion vehicles (ACVs) can break large extents of relatively smooth sheet ice covers, usually in areas where the sheet ice may stop the ice run and initiate a jam. The advantages of an ACV are its speed and maneuverability and its ability to operate in shallow water areas. Disadvantages are that it breaks but does not move the ice, it cannot operate over rough ice accumulations because of potential damages to its flexible skirts, and operation in cold weather can lead to severe icing of the propulsion system.

(6) Construction equipment can be used to break up an ice cover or an existing jam, either from the shore or, if the ice is safe, from the river itself. It is generally best to begin at the downstream end of the ice cover and work upstream, so the broken ice will be carried away by the flow. A heavy weight or wrecking ball can be dropped repeatedly on the ice surface to break up the ice (Figure 12-13). Ice can be broken either to form a channel or weaken the ice in specific locations.

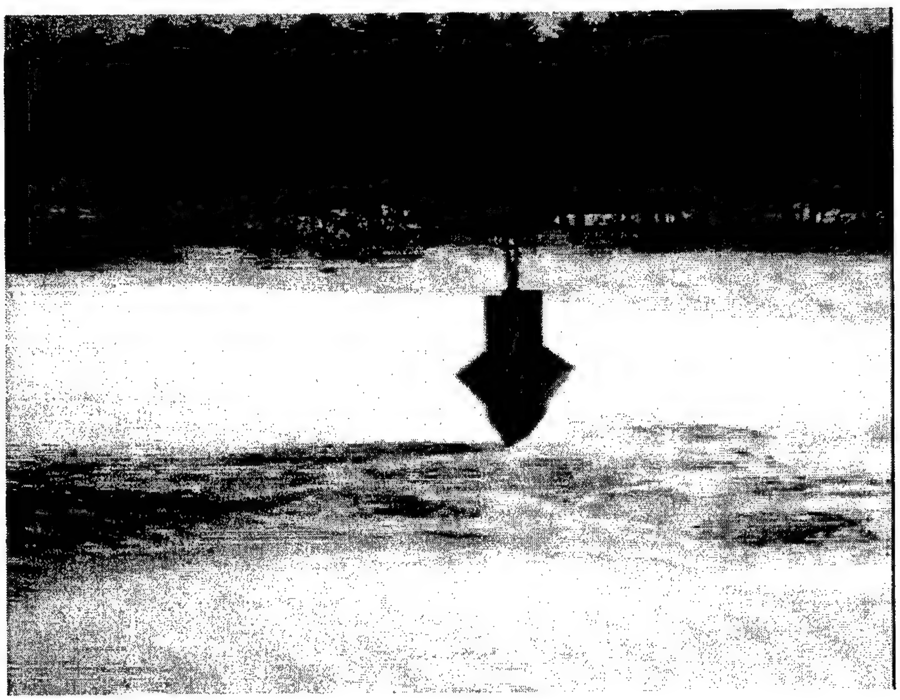
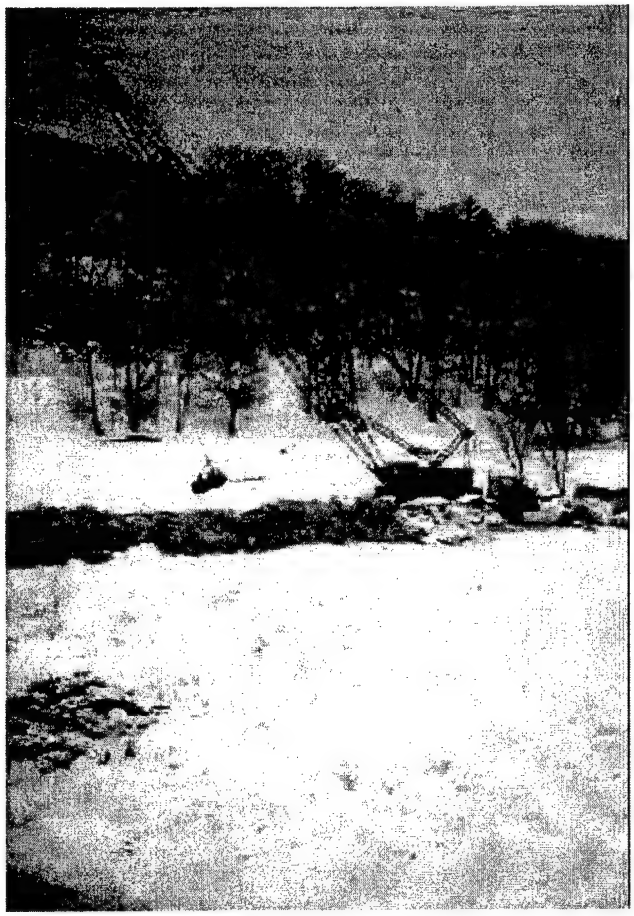


Figure 12-13. Icebreaking using a heavy wedge suspended from a crane

b. Mechanical removal. Mechanical removal involves taking the ice out of the river and placing it elsewhere using bulldozers, backhoes, excavators, or draglines, starting from the downstream end of the ice accumulation (Figure 12-14). This, of course, eliminates any downstream problems, but it is neither cheap nor fast. This approach is most effective on small streams, because the time required to excavate makes the technique prohibitive on larger rivers. Also, there are significant safety concerns associated with equipment operation on wide or deep rivers. The approach is limited to dry jams in relatively shallow streams. In other words, this approach is used generally for midwinter jams on small streams after the flooding has receded. The idea is to create a small channel within the jam. The lack of access for heavy equipment to an ice jam site frequently is an impediment to mechanical removal of ice.

(1) In February 1978 it cost approximately $11,500 (1978 dollars) to make a 790-meter (2600-foot) channel with one Caterpillar 235 backhoe. When the ice blocks are small and thin, mechanical clearing



a. Using a dragline

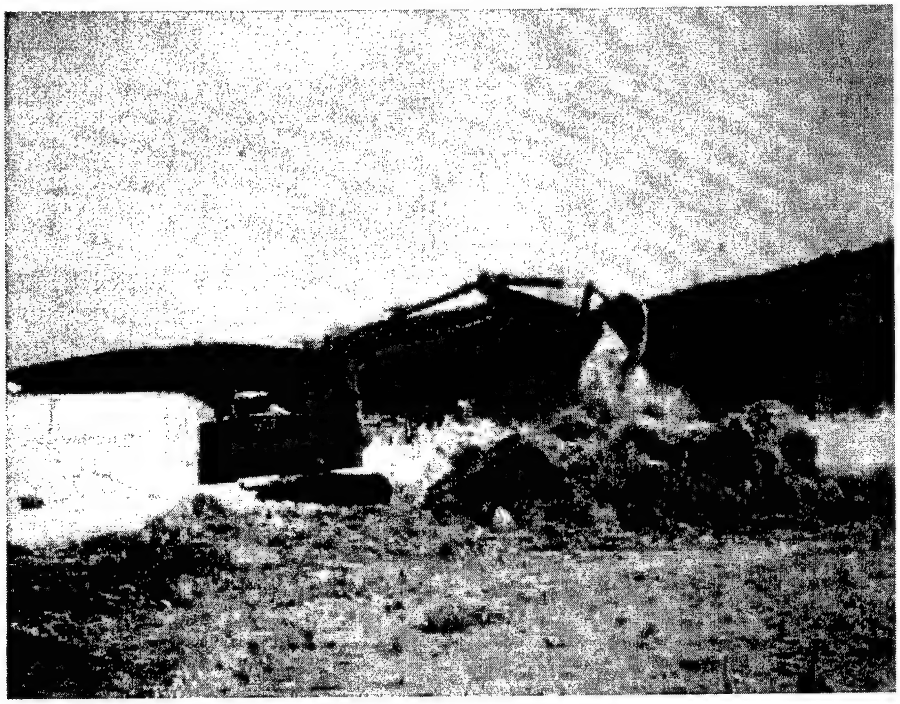
Figure 12-14. Ice removal

does not present too great a problem. When the blocks are around 3.0 × 3.0 × 0.6 meters (10 × 10 × 2 feet) or larger, small equipment is generally inadequate.

(2) Each site is different, so that equipment and methods used are up to the operator, who must be aware of the problems of power lines, poor bottom, and access. An immediate problem is disposing of the ice. Usually, it can be pushed to each side, leaving a channel about one-third the normal river width. In reaches where the channel has been severely restricted by man-made works, it may be necessary to remove all the ice.

c. Ice blasting. A popular solution to ice jam problems, blasting breaks up an ice cover or loosens an ice jam so that it is free to move. Successful blasting takes time and careful planning and execution.

(1) Absolute prerequisites to successful blasting are: 1) enough flow passing down the river to transport the ice away from the site, and 2) sufficient open-water area downstream to receive the ice. Otherwise, the ice will simply re-jam elsewhere and cause problems for another community. Blasting has been used to remove or weaken strong lake ice that initiated breakup jams at tributary–lake confluences, or to create a relief channel within a grounded jam to pass water and decrease upstream



b. With a backhoe

Figure 12-14. (Concluded)

water levels. As with icebreaking and mechanical removal, it is recommended that blasting proceed upstream from the toe of the jam.

(2) The ideal time to blast a jam is just after it has formed. In actuality, a jam is never blasted this quickly because a blasting crew and governmental approval cannot be mobilized until the jam is well formed and flooding has begun. If the flow has dropped because of cold weather or has moved into another channel so that after a blast there will not be enough water to carry the loosened ice downstream, the blasting should be canceled.

(3) While very dramatic, blasting is not a quick or easy solution. Blasting requires planning to locate and acquire the explosives, the equipment to drill holes, and the personnel. At all times when the crew is working on the jam, a lookout should be on duty upstream to sound the alarm if the jam lets go by itself. At least two people are required to drill holes, and depending on the roughness of the surface, at least four more to carry the charges to the holes. Add a blaster, a supervisor, and two people to load the charges and you have a crew of 11. With good luck this crew can blast two rows of charges along 0.8 kilometers (about a half mile) of river per day, possibly more when a routine has been established.

(4) To be effective, the charge should be placed below the surface of the ice, which may be dangerous or impossible during an ice jam event. If the sheet ice or jam is stable, holes can be drilled at regular intervals from the surface to receive the charges. If not, the charges need to be dropped from a helicopter into existing openings (if any) in the ice cover.

(5) To blast from the top of the ice, certain procedures should be followed to maximize the degree of success. It is important that each charge be placed in the water immediately below the ice so that the large

gas bubble resulting from the blast will be most effective in breaking the ice. The charges should be weighted to sink, but also roped to the ice surface so that they remain as close as possible to the ice underside and are prevented from being carried downstream by the current. As shown in Figure 12-15 (adapted from Mellor 1982), the diameter of the hole of the crater in the ice is primarily a function of charge weight, and is relatively independent of ice thickness. For example, a charge size of 18 kilograms (about 40 pounds) will create a hole of 12 to 14 meters (40 to 45 feet) in diameter for ice thicknesses ranging from 0.3 to 1.8 meters (1 to 6 feet). Two more or less parallel rows of charges, set close enough so that the craters intersect, usually give the best results by creating a wide enough channel to preclude most secondary jamming. The thalweg of the river should be located and the blasting line placed along it as much as possible.

(6) Although any kind of explosive can be used, experience has shown that ANFO works well. ANFO is a mixture of fuel oil with ammonium nitrate fertilizer. The mixture must be detonated with a strong booster such as a stick of dynamite, TNT, or other special booster charges sold by powder companies. The ANFO charge must be kept dry, and it is recommended that it be placed in a plastic bag that can also hold the weight (such as a brick or sandbag) necessary to sink the charge. ANFO will dissolve with time if a misfire takes place. This will avoid leaving live charges on the river bottom. As a guide, it is preferable to use Primacord for all downhole and hookup lines. The charge is then set off with one electric cap that is taped to the Primacord at the last moment after the blasting party is off the ice (see Figure 12-16).

(7) Safety and environmental concerns must be addressed before implementation. A formal safety plan covering all operations is necessary. It should comply with both local and Federal regulations. Such matters as person in charge, communication, transportation, warning personnel, etc., should be fully covered. In particular, blasting in populated or developed areas may lead to damages to surrounding buildings from falling ice chunks. In general, blasting should be a last resort.

d. Evacuation. The principle behind evacuation is to move people at risk from a place of relative danger to a place of safety via a route that does not pose significant danger. Local law enforcement departments usually serve as lead organizations employing standard operating procedures. Winter weather conditions should be taken into consideration when planning evacuation timing, equipment, and routes.

e. Levee closing. If ice jam flooding has been predicted, levees should be closed immediately and interior drainage pumps prepared for possible activation. Again, winter weather conditions that can hinder levee closing, such as snow drifts or frozen valves, should be identified. Monitoring water levels at levees may aid in the identification of possible overflow sites before there is serious damage.

f. Sandbagging. Although ice can cause significant damage to sandbags used as protective barriers, the use of sandbagging as an emergency response measure can be very effective in reducing damages at particular facilities or locations. For example, sandbagging around sewage treatment plants or low points on roads or river banks can significantly reduce flood losses (see Figure 12-17).

12-8. Case Studies

In Appendix B, seven case studies are presented that describe the solutions chosen to mitigate ice jamming problems in a wide variety of locations. The methods employed include thermal control, improved natural storage, ice retention, mechanical removal, floating ice booms, revised operational procedures, a

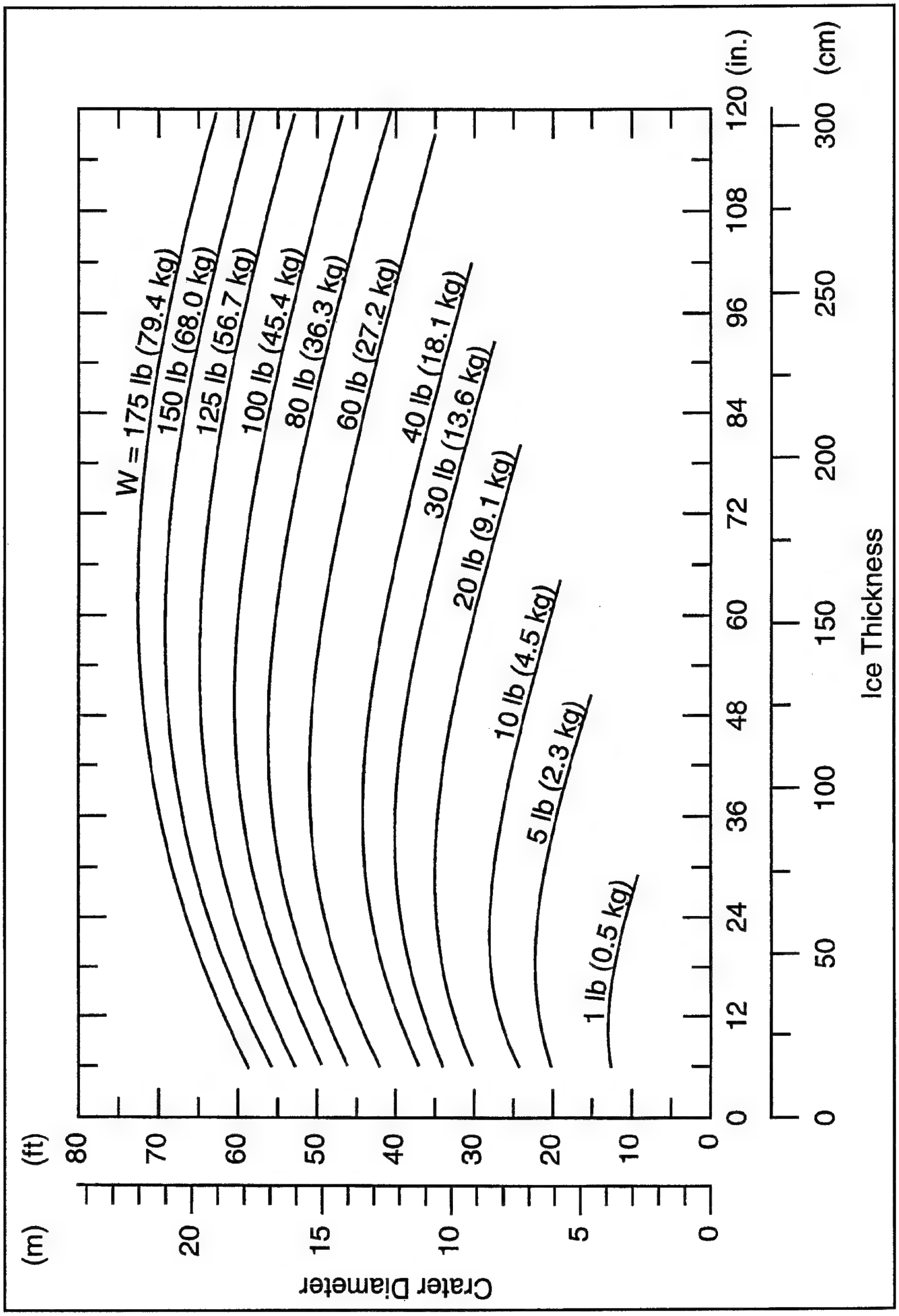


Figure 12-15. Crater hole diameter as a function of ice thickness and charge weight

Figure 12-16. Ice blasting

permanent ice control dam, an ice control weir, land acquisition, aerial dusting, floodproofing, and relocation. Review of these case studies will provide the opportunity to connect ice jam problems with successfully implemented solutions.

12-9. Conclusion

Each measure for dealing with ice jams described in this chapter has its own advantages and disadvantages. The decision as to which method to use may be easy. The difficult problem, particularly in the case of emergency measures, is to decide if any work is necessary. Will the jam go out by itself? How great a hazard really exists? Experience is helpful for this decision, but ice jams are not that common and few people have the opportunity to observe many jams for logical comparison. Thus, advice from local people familiar with the particular stream and its history is invaluable.

12-10. References

a. Required publications.
None.

b. Related publications.

ER 500-1-1
Natural Disaster Procedures

a. To protect sewage treatment plant

Figure 12-17. Use of sandbags in Oil City, Pennsylvania, in anticipation of ice jam flooding

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b. To protect downtown buildings

Figure 12-17. (Concluded)

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Part III: Winter Navigation on Inland Waterways

Chapter 13
River Ice Management Study

Section I
Study Concept

13-1. General

Operational or structural solutions to ice problems on rivers can be applied in several ways. They can be employed individually, case by case, to overcome the ice problems that are regarded as most important on a given waterway or portion thereof. This approach will solve ice problems, and in so doing, it will improve winter navigation. However, a shift of emphasis, from solving individual ice problems to maximizing the overall efficiency of winter navigation on an entire waterway, is a better technique; this results in the need for a comprehensive, system-wide approach. This system approach is essentially a planning process, culminating in the development of a River Ice Management (RIM) Plan that is unique for the waterway in question.

13-2. Objectives

The planning process works toward three objectives. First, winter navigation is to be conducted with the highest possible efficiency, approaching that of the other seasons of the year. Second, ice interruptions to navigation are to be kept as infrequent and as short as possible. Third, if a specific ice emergency does happen, all reasonable and possible ice-problem solutions will have been identified and implemented where appropriate, with the assurance that no further action could be taken to alleviate the emergency.

13-3. Elements

In the remainder of this chapter, the elements of a study leading to a River Ice Management Plan are identified and discussed briefly. Appendix C summarizes the elements in outline form. In the remaining chapters of the manual, these several elements, which include the various operational and structural solutions to river ice problems affecting navigation, are addressed in much greater detail and, in several instances, illustrated by examples.

Section II
Study Elements

13-4. River System Definition

Managing river ice is almost a basin-wide effort; so, knowing the exact configuration of the river system is very important. The primary concern is the main, navigable stem of the river. However, non-navigable reaches of the main stem that are bypassed by locks and canals are also of major interest. It is necessary to know what percentage of the flow goes through each section and what the water velocities are. The tributaries are of interest because they add ice to the system. Also to be identified are any features that affect ice passage or accumulation, e.g., channel geometry, confluences, and man-made or natural channel restrictions.

13-5. Ice Problem Identification

Proper implementation of a winter navigation plan requires that problems be identified, along with their locations and sources (see Chapter 14).

a. Certain problems are natural phenomena and are inherent to navigation during winter months. Ice jams may limit passage through a section of river. Ice accumulation in the upstream approaches at many locks causes shipping delays as vessels must wait for ice to be locked through.

b. Other problems are more directly induced by winter navigation. Ice builds up on the undersides of barges, sometimes resulting in scraping and damage to the riverbed or miter gate sills. Barges having underside ice buildup have grounded and blocked channels on the Upper Mississippi River, and the normal dredging response to a grounding is very difficult under ice conditions. Moored barges may be broken away by moving ice, resulting in damage to downstream structures. Increased traffic during periods of ice may increase bank erosion significantly.

c. The source of the ice that creates the problem needs to be identified. Possible ice sources include tributaries, upstream locks and dams passing ice, and vessels traveling out of established tracks. Once these ice problems and their ice sources are identified, an appropriate solution, whether operational or structural, can be considered. Not to be overlooked are possible future changes in the river system that may have an influence on ice formation (e.g., changes in water quality affecting freezing temperature).

d. All possible scenarios are to be considered in implementing a winter navigation plan. Past ice emergencies on the river system in question should be thoroughly examined. Emergencies have been avoided by varying operational schemes. Solutions to ice emergencies on other river systems should also be examined, so that nothing is overlooked. Once a winter navigation plan is developed, it should be analyzed with all possible ice emergencies in mind and revised as necessary.

13-6. Ice Forecasting

Forecasting river ice conditions means predicting when and where ice will form, how thick it will be, the extent of the ice cover, and how long it will last. Practically, there are two types of river ice forecasts. The first is a *Long-Term Water Temperature Forecast.* This is made (starting in the fall) to predict river water temperatures to determine when the water will reach the freezing point, making ice formation possible. The present water temperature at the time the Long-Term Water Temperature Forecast is made must be known, and a forecast of air temperatures must be made or be available. The water temperature response to changes in the air temperature can be determined by examining records of water and air temperature of previous years. This type of forecast can be made for periods of several days to several months. The second type of forecast is a *Mid-Winter Ice Forecast.* Typically, these are made for periods of a week or less, predicting the water temperature, the volume of ice that will be formed or melted, where the ice will form or melt, the extent of the river that will be covered with ice, and the ice thickness. To make a Mid-Winter Ice Forecast, the existing stages, discharges, water temperatures, and ice conditions along a river must be known. Forecasts of the air temperature, tributary discharge, and tributary water temperature must also be made or be available. Locations and amounts of possible artificial heat inputs into the river must be known. A heat balance can be determined for the river system that will indicate the volume of ice that will be formed or melted. The extent of the ice cover and its thickness are calculated using the river velocity, flow depth, and type of ice. The Mid-Winter Ice Forecast will produce forecasts of the discharge, stage, ice thickness, and water temperature at each point specified along the river. Under the RIM

Program, forecasting methodologies to produce both types of forecasts were developed, and are described in greater detail in Chapter 15. Each has the ability to include real-time data provided by Corps data systems, to incorporate short-term and long-term forecasts of air temperature, and to provide the specified outputs.

13-7. Structural Solutions

Structural solutions are covered in detail in Chapter 3 and additionally in Chapter 18. In brief, they involve controlling ice by installing some type of structure or device where it will have a desired effect on either an ice cover, ice floes, brash ice, frazil ice, or ice adhering to navigation structure surfaces. The desired effect may be to divert ice away from the main channel, to prevent ice from moving out into the channel, to keep an ice cover from being broken up by wind and wave action or by ship activities, to reduce the quantities of ice passing a particular point, or to reduce the amount of frazil ice forming in a reach. In the vicinity of a navigation structure, the objective may be to block or divert moving ice from a lock entrance, to pass ice from the pool through the dam to the channel below, or to reduce or eliminate adfreezing on walls, gates, and other surfaces.

a. A common structural solution is an ice boom, which is a line of floating logs or pontoons across a waterway used to collect ice and stop ice movement (a navigable pass can be provided in the boom). The boom is held in place by a wire rope structure and buried anchors. Other solutions may use weirs or groins supplemented by booms. Artificial islands and navigation piers can also be helpful in stabilizing ice covers. The various methods for inducing a stable ice cover to form are used in locations where ice covers need to have additional stability to compensate for the disruptive forces of winter navigation or short-term weather changes.

b. Structural solutions in and around navigation projects include devices that are installed to help mitigate particular ice problems that pose a direct interference to project operation. High-flow air systems are effective in deflecting and moving brash ice away from critical locations in a great variety of circumstances. Flow inducers have also been installed in lock chambers to assist in keeping areas ice-free. Ice passage at navigation dams is made more practical by certain structural features, such as submergible dam gates, or bulkheads, which can be raised from lock chamber floors to serve as skimming weirs for passing ice. Ice accumulation on critical surfaces such as gate recess walls, strut arm roller rails, and seals can be effectively controlled by installing electrical heating devices of several specialized designs. Other proven measures for controlling ice accumulation on structure surfaces are coatings and claddings. Coatings, such as epoxies and copolymers, reduce ice adhesion forces between ice and concrete or steel surfaces. Claddings, such as high-density polyethylene, are replaceable surfaces from which ice can be chipped more easily than from concrete or steel.

c. Each of the possible structural approaches is effective for a particular ice problem. Many ice problems require a combination of structural solutions, often teamed with operational solutions, to fully mitigate the difficulties imposed by ice.

13-8. Operational Solutions

There are various operational techniques to control or mitigate ice problems at navigation projects. Thermal methods are presented in Chapter 3, Section II, with additional discussion specific to navigation projects in Chapter 18, Section III, and Chapter 19, Section III. Additionally, when lock and dam personnel apply the structural solutions as mentioned above or described in Chapters 3 and 18, these applications actually become operational techniques in themselves.

a. Moving tows in convoy, i.e., scheduling vessels to move together in large groups during periods of heavy ice conditions, has been shown to hold some promise for the navigation industry. The appeal of this to the Corps is that it can cause less ice to be produced in a winter season, and thus reduce the amount of ice that has to be locked through, diverted, or passed at a navigation project.

b. At locks and dams, the operational techniques vary from physical ice removal using various tools, to flushing ice from critical areas with towboat propwash and passing ice through the dam spillway gates. Separate lockages of ice are sometimes required to accommodate tow traffic. Maintaining high lock chamber pool levels can keep lock walls at a higher temperature than if they were exposed to cold air. As a result, ice buildup on the wall surfaces may be lessened. Careful operation of seal heaters aids substantially in reducing ice buildups at dam gates, helping to keep the gates operational.

c. Warm water discharges offer opportunities for ice suppression at certain locations. The warm water may originate from power plant cooling systems, industrial plants, or reservoir discharges. The distributions of these warm inflows influence their effectiveness in melting or weakening ice, or in maintaining open-water areas.

d. Energy from unconventional sources, such as heat from groundwater, solar heating, or wind energy, has been thought to offer promise for ice control at navigation projects. However, analyses have shown that this would be likely only in a very few restricted cases. Nonetheless, electrical heating appears to be the most efficient way to accomplish many ice control tasks at navigation projects. The key is to select the most practical source for electrical energy.

13-9. Recommended Plan

The objective of the study or system analysis, composed of the foregoing study elements, is to develop a River Ice Management Plan. In practice, it may be more reasonable to develop several alternative plans, each of which may have attractive features. While it may not be possible to apply a strict benefit–cost analysis to most ice management plans, such criteria should at least guide the choices of the feasible alternative plans from among the many variations and versions examined. Generally, it will be possible to select one of the alternative plans as the most desirable, in that it provides the highest net benefit or is most likely to eliminate chances for ice emergencies. This is then designated the Recommended Plan. The Recommended Plan may include, among other things, structural measures for improving the winter capabilities of navigation projects. For reasons of financial, personnel, and time resources, a realistic time span must be assumed to accomplish these structural improvements. Therefore, it would be most reasonable to express the Recommended Plan in terms of phases, with the individual phases chosen and ordered according to their anticipated individual benefit–cost ratios. In simple terms, as outlined in Appendix C, a system approach covering many study elements leads to a Recommended River Ice Management Plan for a given waterway or part thereof. The Recommended Plan then serves as a goal toward which subsequent operational and structural decisions lead, resulting in increased efficiency of winter navigation and the supporting operation of navigation projects.

Chapter 14
River Ice Problem Identification

14-1. Surveys Needed

To fully understand the ice processes involved and their effects on winter navigation, the entire river system needs to be fully defined. A general survey of the river system should be made, defining its hydraulic characteristics under open-water conditions, as well as how these characteristics change in times of ice. This survey should indicate how extensive the ice problems are and where they are most concentrated. Areas of ice generation, growth, and deposition, as well as ice-cover initiation points, should be identified. All tributaries must be considered to determine their ice inputs during freezeup, throughout the winter, and during breakup periods. Existing hydraulic structures, such as navigation dams, locks, or hydropower installations, should be examined to see how they influence the river system under present operating procedures. Can these structures control flow? Do they retard velocities, thereby causing ice deposition? Which dams pass ice and how do they pass ice? What influence does ice passed through a dam have on ice problems downstream? What facilities exist for ice passage at locks and dams? Some dams may only be able to pass ice during high flows, while other structures use the auxiliary lock chamber for routinely passing ice. Questionnaire-type surveys can be employed to gain the information outlined above (Haynes et al. 1993, Zufelt and Calkins 1985). These surveys should poll river users as well as the operators of any structures. These and subsequent interviews with specific users will yield information about things such as areas of ice cover, areas of ice generation, ice thicknesses, types of ice, and restrictions to flow and ice passage. Ice problem locations can be identified, as well as other areas of concern, i.e., high traffic areas, temporary fleeting areas, etc.

14-2. Hydrology and Hydraulic Studies

Records should be examined to determine if there have been any previous hydrological or hydraulic studies of portions of the river system. Flood insurance studies, working numerical hydraulic models, navigation models, and backwater studies may offer data on flow velocities, discharges, stages, operational procedures, etc. Some existing mathematical models (such as HEC-2) have been adapted to incorporate an ice cover into the system. Rainfall and snowmelt runoff models for tributaries may give insight into when and with what magnitude the ice cover will break up. Past physical model studies of navigation structures or hydropower installations can give insight into ice movement, accumulation, and passage, as well as ice effects on tows. Ice retention in tributaries and non-navigable main stem reaches must be studied. Existing and planned physical models can incorporate ice studies into their modeling sequence. In conducting any hydraulic or hydrological studies, it is important to obtain as much information on the ice characteristics of the river system as possible. Winter field observations are an invaluable source of information on ice thicknesses and areas of ice cover. Operational logs of lock and dam facilities usually contain information on weather and waterway conditions. Hydropower and other power plants, as well as water supply or treatment plants, often keep records of water and air temperatures, along with ice conditions at their intake or outfall structures. Towing companies sometimes keep records of ice conditions, especially when they affect shipping schedules. River users and structure operators generally have a good knowledge of average winter ice conditions and these people should be interviewed.

14-3. Identification of Ice Problems

Ice problems should be identified by type, location, and severity. On-site observations of the problem areas are also useful. A survey questionnaire to poll river users and structure operators is quite valuable. A sample questionnaire is shown in Figure 14-1.

1. Location: River ____________
   Mile ____________

2. Hydraulic structure: No ______ Yes ____________
   Name ____________

3. Problem area: Bend ____________
   Island(s) ____________
   Spillway Gates ____________
   Lock Gates and/or Approaches ______

4. Description of problem: (use reverse side if necessary)
   ____
   ____
   ____

5. Documentation available: Reports* ____________
   Memos* ____________
   Individuals ____________
   (*copies appreciated if available)

6. Have there been any attempts to alleviate the problem?
   No _____ Yes _____
   If yes, Re-design ____________
   Operational changes ____________
   Reports ____________

7. How does this problem rank with other ice problems in your jurisdiction in its impact on the operation of the structure/river system?
   High ____________
   Medium ____________
   Low ____________

8. Identify any structures that have been specifically designed, modified, or retrofitted to alleviate this ice problem:
   Site | Point of Contact | Address & Telephone Number

Figure 14-1. Questionnaire for collecting information on ice problems affecting navigation projects and navigational activities

a. Information sources. Aerial photos and video coverage of the river system during winter can provide data on problem type and location, although problem severity is best estimated by those with firsthand knowledge of the area. Lockmasters, towboat operators, and homeowners adjacent to the area in question are an excellent source of data and should be polled or interviewed as necessary. Operations personnel are usually well informed of problem areas, including emergency conditions.

b. Problem categories. There are two general problem categories: those occurring at or near navigation structures, and those occurring in the river pools between navigation structures. Navigation dams may experience limited ability to pass ice moving downstream because of gate-setting limitations. Spillway gates may ice up because of leaking seals or normal operations, resulting in restrictions in movement, overstressing of structural components, or even inoperability. Lock facilities may experience ice accumulations in the upper and lower approaches or behind miter gates, slowing operations

significantly. Ice may adhere to the lock miter gates, lock walls, line hooks, vertical checkpins, or floating mooring bitts, resulting in increased winter maintenance. Problems generally associated with areas away from navigation structures include severe ice accumulations or jams near islands and bends, tributary ice inflows, and problems encountered near docks and fleeting areas. Following are detailed descriptions of typical ice problems that have been reported in the past. This list, however, is not all-inclusive.

14-4. Ice Problems Around Navigation Projects

a. Ice in upper lock approach. Broken ice, carried downstream by the river current and wind, or pushed ahead of tows, often accumulates in the upper lock approach, causing delays (Figure 14-2). Separate ice lockages often must precede the locking of downbound tows, and flushing ice during these ice lockages is difficult. Occasionally, a tow must back out of the lock after entry because the ice doesn't compact in the chamber as much as expected, preventing the tow from fully entering the lock chamber and thus causing further delays. Upbound tows may have to limit their size to be assured of enough power to push through the accumulations of ice. Tow haulage units usually have too little power to pull the first cuts of double lockages out of the chamber against heavy accumulations of ice. So, double trips or smaller tows are called for. During periods of low traffic, ice accumulations sometimes freeze in place, causing further delays and difficulty in operating the upper gates.

Figure 14-2. Ice accumulation in the upper lock approach area

b. Lock miter gates. Ice accumulations in the upper lock approach can cause pieces of ice to become wedged between the miter gates and the wall recesses (Figure 14-3). Ice pushed into the lock chamber ahead of downbound tows causes the same difficulties for the lower gates. The gates must be fanned or the ice pieces prodded with pike poles to make them move out of the way. Sometimes, compressed air lances or steam jets are used to disperse the trapped ice.

c. Ice buildup on lock walls and miter gates. During extremely cold weather, and with fluctuating water levels in lock chambers, ice will build up on the lock walls and miter gates, forming a collar (Figure 14-4). This collar is thickest at the upper pool level. Enough ice can build up on the walls to keep the gates from being fully opened, thus limiting the width of tows and leaving the gates exposed to

Figure 14-3. Broken ice accumulation between the lower miter gate and the gate recess wall, which hinders full recessing of the gate

damage. Even where the buildup is minimized or controlled in the gate recesses, ice on the chamber walls can be thick enough to restrict tow widths. Most of the inland waterways that have barge traffic can place width restrictions on the lock chambers. This is not desirable, but at least it allows navigation to continue with narrower tows. (On river systems such as the St. Marys or the St. Lawrence, however, the usable width of the locks is critically important, because the vessel widths can't be reduced.)

d. Floating mooring bitts. Ice pieces may jam between the floating mooring bitts and the lock wall, rendering the bitts inoperative. Ice layers may build up on the wheels, track, or flotation tank of a bitt (Figure 14-5), causing the bitt to freeze in place; the bitt can then dangerously and unexpectedly jump upward from its submerged position. Usually, bitts must be tied off at the top of the lock wall and remain unavailable for winter use.

e. Vertical checkpins or line hooks. The vertical checkpins or line hooks in the lock walls may accumulate layers of ice because of fluctuating water levels. This causes difficulties when check lines slip and jump off the pins or hooks.

Figure 14-4. Ice collar formation on the gate recess and chamber walls, restricting the full opening of the miter gates and limiting the usable width of the lock

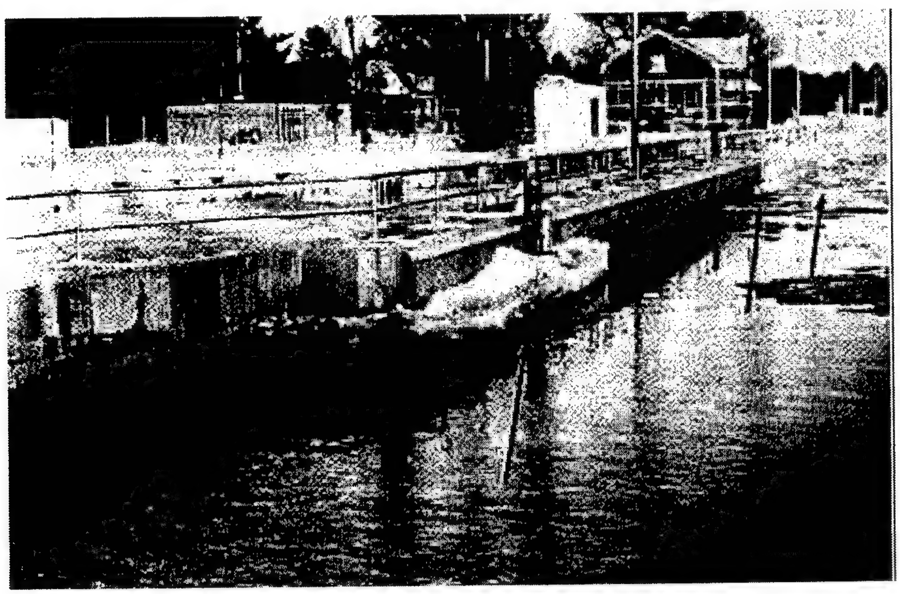

Figure 14-5. Ice interference with floating mooring bitts (arrows) in a lock chamber wall

f. Ice in lower lock approach. Ice may accumulate downstream of a lock because of upstream wind, or an island, bend, or other constriction. Ice passing through the lock or over the spillway adds to this accumulation. The continual buildup of ice may block the entrance to the lock for upbound tows.

g. Dam spillway gates. Broken ice carried downstream usually accumulates at the dam (Figure 14-6). During periods of low flow, normal gate openings are small and will not pass this ice. Low tailwater presents a problem of excessive scour if gates are raised high enough to pass the ice. In colder weather, these accumulations will freeze in place, making it necessary to break up the ice to start it or keep it moving (usually done by towboats). Some lock and dam facilities have been equipped with submergible tainter gates specifically designed for passing ice and drift. At a few installations, the gates are rarely used in the submerged settings, owing to excessive vibrations that could cause damage to the gate and supporting structure of the dam. Some of these submergible gates have been retrofitted to prevent them from being used in the submerged position. Other lock and dam facilities report no problems with operating these gates in the submerged position. A feature of all submergible gates is that they leak more than nonsubmergible gates. In winter, freezing of this leakage adds to the problems described in the following two paragraphs. Three installations on the Monongahela River are equipped with split-leaf (movable crest) tainter gates, designed for passing ice and debris. The gates seem to work well, but during periods of low flow, towboat assistance is required to break up the ice behind the dam and start it moving. Lock and Dam No. 16 on the Mississippi has reported that an emergency bulkhead placed in the entrance to a roller gate bay passes ice well.

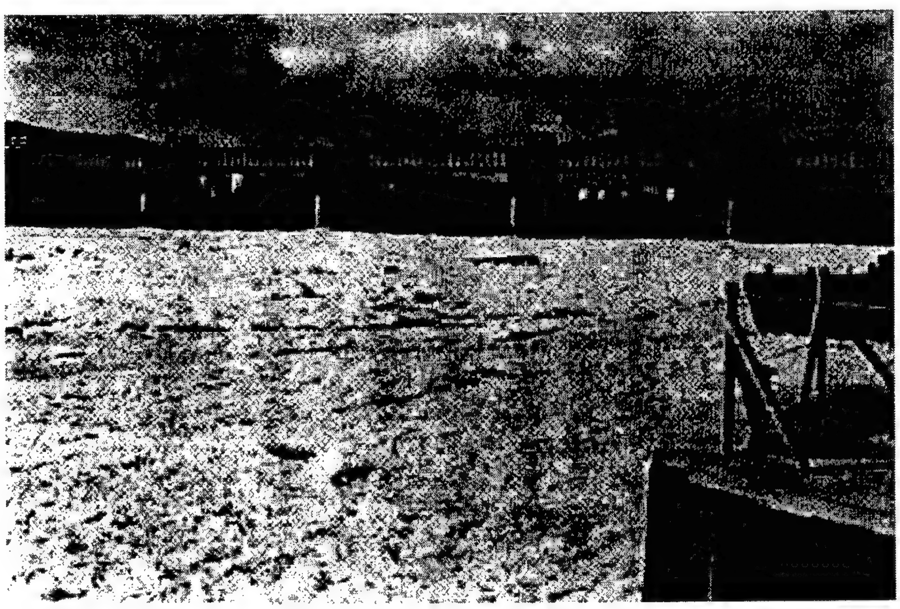

Figure 14-6. Ice accumulation upstream of the gates of a navigation dam

h. Spray icing of spillway gates. Spray from the operation of spillway gates can cause ice to form on the pier walls or under the arms of tainter gates (Figure 14-7). This may cause jamming or stop the gates from fully closing. In some cases, the weight of ice formed on the gate structure is so great that the operating machinery cannot raise the gate.

i. Tainter gate seals. The side and bottom seals of tainter spillway gates may leak, causing spray. This spray results in ice buildup on the pier walls or the gates themselves, causing operational difficulty

Figure 14-7. Tainter gate structure and gate pier wall with icing that has accumulated through spray and splashing in the course of winter operation

(Figure 14-8). It is possible for this ice to bridge across from the pier to the gate, rendering the gate seal heaters ineffective. During severe cold, the gates must be moved frequently or they will freeze in place. Attempts to operate gates when frozen in place can result in damage to the operating machinery, hoisting mechanisms, and chains or cables.

j. Ice formation on intake trash racks. Broken ice and frazil ice can accumulate on trash racks, causing a reduction in flow. This results in loss of water supply and possible shutdown if flows are substantially blocked. In the case of hydropower intakes, power production may be interrupted.

14-5. Ice Problems Occurring Between Navigation Projects

The channels around islands, bends, and other constrictions tend to accumulate thick deposits of ice (Figure 14-9). During periods of significant ice, these accumulations may form jams, which can cause scouring and eroding of bed and banks. Navigation can be interrupted or delayed and structural damage is possible, especially during breakup of the jam. Minor jams may raise the water level upstream, while major jams can cause severe flooding. Tows must limit their size in some problem areas.

a. River bends. River bends are often the cause of ice accumulation. The nonuniformity of depth and velocity over a bend cross section, coupled with secondary flow circulation, results in a nonuniform ice cover. Under open-water conditions, multiple cells of secondary currents are set up that, in general, push surface water toward the outside of bends and bed material toward the inside of bends (Figure 14-10). If these same circulations exist under ice conditions, one would expect thick accumulations on the outside of bends, while the relatively tranquil flow on the inside of the bend would allow shore ice to form easily, reducing the open surface width. Limited laboratory experiments (with a fixed bed) have shown that these secondary currents may be modified by the presence of an ice cover, further compounding the nonuniformity of the ice cover. In addition to this nonuniformity, vessels often have

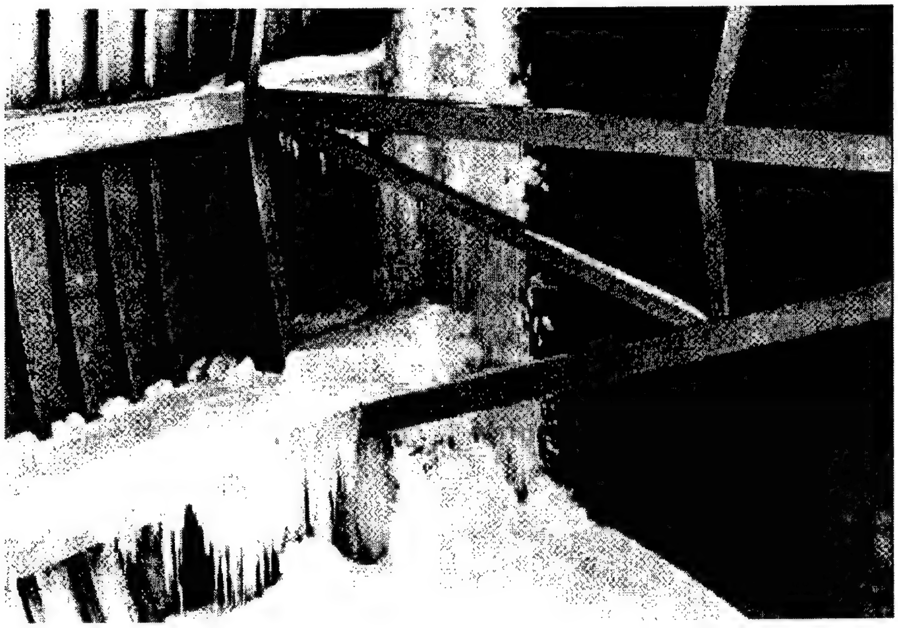

Figure 14-8. Tainter gate frozen in place by ice formed by leakage past the gate's side seals

Figure 14-9. Heavy accumulations of ice floes and brash ice

trouble tracking around bends under ice conditions, particularly severe bends as on the upper Monongahela River. Figure 14-11 shows a vessel track around a severe bend. Note the wide, irregular appearance of the track caused by transiting problems. Experience in the Pittsburgh District indicates that river bends having 110 degrees or more of curvature will cause transiting difficulties when ice is present.

b. Reduced open width of river surface. Laboratory experiments with plastic "ice" have shown that there is a relationship between the characteristic size of ice floes and the open width of a channel for the occurrence of arching and channel blockage. Once blockage has taken place, an accumulation of surface

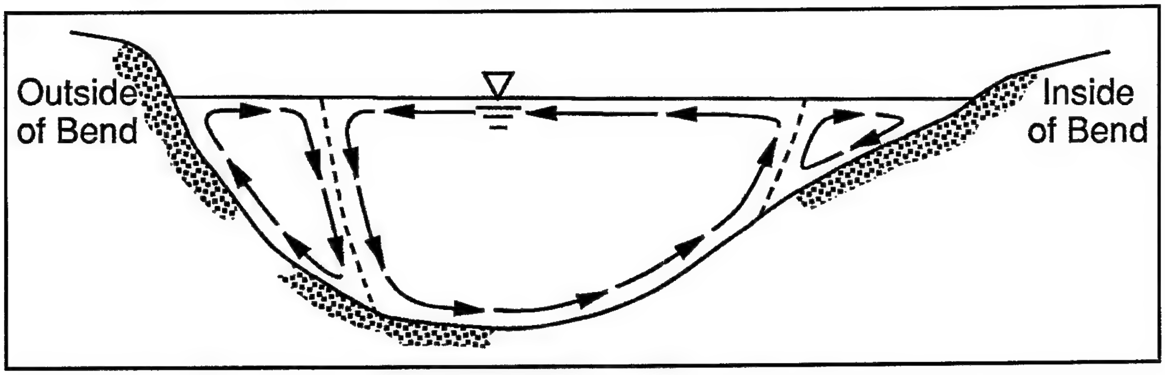

Figure 14-10. Transverse velocities forming secondary circulation cells in river bends

Figure 14-11. Broken, irregular vessel track around a sharp river bend, indicating difficulties in navigating through the ice

floes may progress upstream. One mechanism that accelerates the blockage process is the growth of shore ice, which reduces the open width of the river surface. The shore spans of bridges often freeze over quickly during periods of low flow, and this width reduction may be enough to cause blockage when ice discharge in the river is high. Figure 14-12 shows the Allegheny River at Pittsburgh, Pennsylvania, where the open surface width has been reduced significantly by the freeze-over of the shore spans of several bridges. Islands may also cause a reduction in open surface width. Typically, one channel around an island carries the major portion of flow while the other freezes over. Again, this surface-width reduction may be enough to initiate blockage. Figure 14-13 shows an island with one of the channels frozen over.

c. Tributaries. During breakup, tributaries may discharge large quantities of ice into the main river. If the main river is still frozen or partially ice-covered, an accumulation may result. On a large scale, this is what happens when the Monongahela River breaks up, discharging ice into the Ohio River. Typically, only the larger tributaries are significant and the duration of this type of problem is small. Very steep

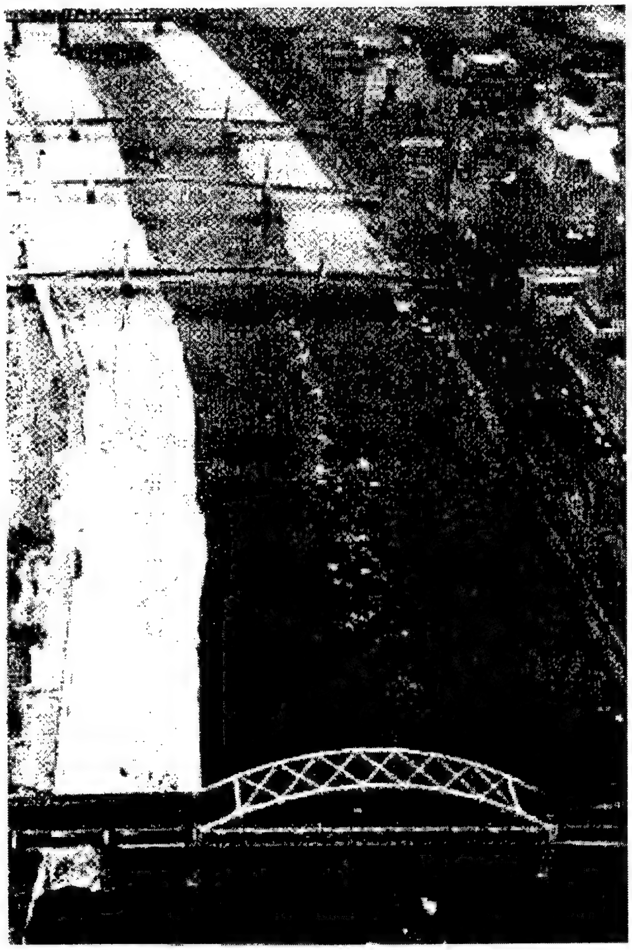

Figure 14-12. Shore ice formation, with bridge piers providing added stability to the shore ice

tributaries may remain open all winter long, generating large quantities of frazil ice. The upper reaches of the Allegheny River (above Lock and Dam No. 9) supply frazil to downstream areas through the winter. Tributaries, whether large or small, may also have fans or bars extending into the main river. These shallower areas tend to freeze over quickly, extending shore ice into the river and reducing the open surface width. A special case exists on the Illinois Waterway in the vicinity of Marseilles Lock and Dam. The river is split by a long island, with the dam at the upstream end of one channel (the north channel) and the lock at the downstream end of the other (the south channel). The north channel is fairly steep and generates frazil ice all winter long. The south or navigation channel is flat and generally freezes as a lake. A short distance downstream of the lock, the two channels rejoin with a flat slope. The frazil moving down the steep north channel suddenly loses velocity and tends to accumulate downstream of the junction. Accumulations in this area can reach thicknesses of 1.8 meters (6 feet) and lengths of 0.8 kilometer (1/2 mile). It is not unusual for towboats to spend 10 to 18 hours to navigate through this section.

d. Fleeting and mooring areas. Under midwinter conditions, there is often a narrow shipping track that remains open following the channel line in an otherwise frozen river. This is characteristic of the

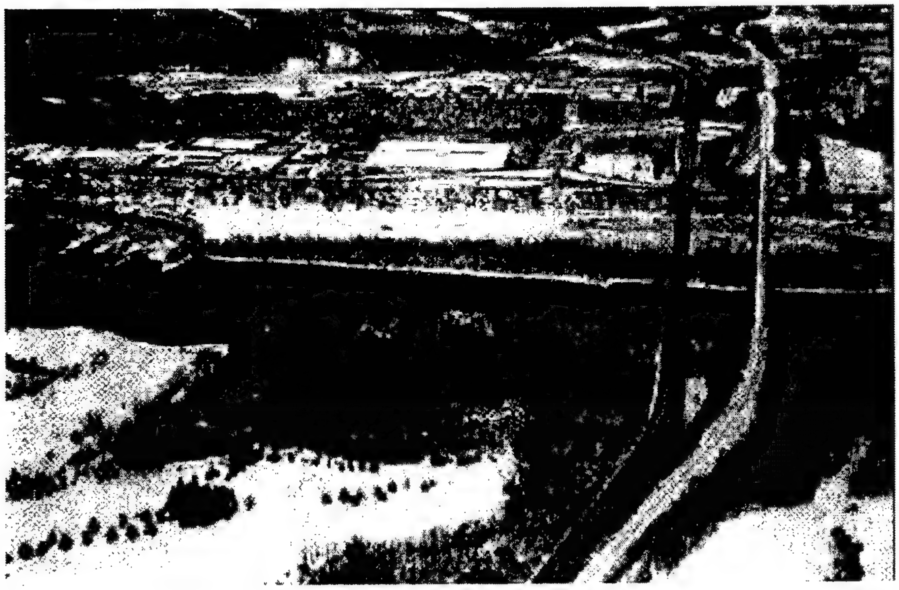

Figure 14-13. River divided into two channels by an island; the main channel is open while the secondary or back channel is ice covered

upper Monongahela River. Tows travel in these established tracks, leaving them only to move to mooring cells, fleeting areas, or docks. If care is not taken to move to these areas by additional established tracks, large ice pieces can be broken away from the cover and become lodged in the main shipping track. Figure 14-14 shows a fleeting area near shore and an established navigation track following the shipping channel.

Figure 14-14. Navigation track in the middle of the channel, with a fleeting area at the near bank; traffic using the fleeting area can break free large floes that can move out to block the track

14-6. References

a. Required publications.
None.

b. Related publications.

Haynes et al. 1993
Haynes, F.D., R. Haehnel, and L. Zabilansky. 1993. *Icing Problems at Corps Projects*, Technical Report REMR-HY-10, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Zufelt and Calkins 1985
Zufelt, J., and D. Calkins. 1985. *Survey of Ice Problem Areas in Navigable Waterways*, Special Report 85-2, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Chapter 15
Ice Forecasting

15-1. General

Forecasting of ice conditions on inland waterways is based on the premise that, given forecasts of future meteorological conditions and forecasts of future hydraulic conditions, it is possible, through knowledge of thermodynamics, open channel hydraulics, ice physics, and an understanding of the behavior of the various forms of river ice, to develop forecasts of the future ice conditions. The methodology described in this chapter produces ice forecasts that are unique to a specific river or basin for which an Ice Forecasting System is developed.

a. The first goal of an Ice Forecasting System is to anticipate the period when ice formation is possible and, if possible, assign probabilities to the likelihood of formation. This type of forecast is known as a Long-Term Water Temperature Forecast. Such forecasts are made by a computer model of the overall heat balance of the river watershed, which indicates the long-term water temperature response to changes in air temperature.

b. A second type of forecast is much more detailed in its results. The goals of this type of forecast are to predict the reaches of a river where ice will form, when that ice will form, the areal extent of stationary ice, the ice thickness, the time of breakup, and ice jams and other extreme ice conditions. This Mid-Winter Ice Forecast is very sensitive to day-to-day changes in meteorological conditions and flow conditions, making it apply to a much shorter time, generally 5 to 7 days. This short-term forecast requires the development of three closely interrelated models: first, a dynamic flow model to simulate the channel hydraulics, including the influence of ice; second, a thermodynamic model to simulate the heat transfer between the waterway and the atmosphere; and third, an ice formation model to distribute the ice along the waterway and to calculate the ice thickness.

c. In this chapter, general overviews of the Ice Forecasting System, including the Long-Term Water Temperature Forecasts and the Mid-Winter Ice Forecasts, are presented. For each type of forecast, its objective, the basic theory, the model operation, the data required for model calibration, the data required for model operation, and the results are discussed.

Section I
Long-Term Water Temperature Forecasts

15-2. Objective

Predictions of water temperature are made primarily to estimate when the water temperature will be at or near the freezing temperature, 0°C (32°F). It is at this time that ice can be expected to form. Advance knowledge of the date that freezing temperatures will be reached allows efficient management of resources necessary to deal with the problems that can be caused by ice at locks and dams and other Corps facilities, and may assist operational planning for other navigation interests.

15-3. Model Description

River water temperatures reflect the balance of heat flow into and out of the volume of water that makes up the river discharge. This principle forms the basis of river water temperature forecasting. At any point

along a river, the water temperature at that point reflects the heat balance upstream of that point. Mathematically, this temperature can be represented by a convection–diffusion equation. However, this equation can require a great deal of information to solve, and much of the information may not be known for future times. An efficient alternative is a total watershed approach. This approach assumes the following:

- The temperature of the river is well-mixed vertically; that is, the temperature of the river is uniform from the surface to the bottom. (This will be true of almost all rivers with any velocity. This may not be true of reservoirs, lakes, or other large bodies of water without appreciable flow velocity.)

- The heat flow into and out of the river water is dominated by exchanges with the atmosphere. (This allows the prediction of the river water temperatures to be based on forecasts of future meteorological conditions. Other heat sources, such as industrial or municipal effluents, can be factored into the forecast by studying past response of the river water temperature. However, if the water temperature of the river upstream of the point for which the forecast is to be made is dominated by such sources, this approach may lead to large inaccuracies.)

- The river is essentially free-flowing, having only a relatively small portion of its drainage area covered by reservoirs or lakes, the temperatures of which are not dominated by artificial heat sources.

a. Heat transfer components. There are many components of the heat balance that affect and determine the actual resulting river water temperature. These include heat transfer to the atmosphere, heat transfer to the ground, the influx of groundwater, and artificial heat sources. As stated previously, the heat transfer is dominated by the exchange with the atmosphere. This exchange has many modes, including long-wave radiation, short-wave radiation, evaporation, condensation, and precipitation. However, many of these modes are difficult to forecast, and forecasts of them are not generally made. Therefore, a simple but generally accurate means of approximating the heat transfer rate ϕ is made based on the equation

$$\phi = h_{wa}(T_w - T_a) + q \tag{15-1}$$

where

T_a = temperature of the air

T_w = temperature of the water

h_{wa} = effective heat transfer coefficient from the water to air

q = heat inflow that is independent of the air temperature, such as solar radiation.

b. Convection–diffusion equation. In this watershed approach, the one-dimensional convection–diffusion equation can be simplified to the form

$$\frac{DT_w}{Dt} = -\frac{\phi}{\rho C_p D} \tag{15-2}$$

where

D/Dt = total derivative

ρ = density of water

C_p = specific heat of water

D = mean channel depth.

c. Air Temperature Representation. In principle, the average daily air temperature over the entire period of a year can be represented by a Fourier series. However, in practice, it is efficient to represent the actual mean air temperature on any day by

$$T_a = \bar{T} + \alpha \sin\left(\frac{2\pi t}{T} + \theta\right) + T_{\delta_j} \tag{15-3}$$

where

t = Julian date

T = number of days in year (365 or 366)

θ = phase angle

$\bar{T}$ = mean annual air temperature

a = amplitude

$T_{\delta j}$ = deviation in air temperature.

The deviation in air temperature represents the difference between the actual daily average air temperature and the sum of the yearly mean temperature and the first harmonic representation of the daily average air temperature. The values of T, a, and θ can be found by analyzing air temperature records from previous years that have been collected in the region where the water temperature forecasts are to be made. Examples are shown in Table 15-1. The deviations of daily average temperature from the first harmonic representation for all past data can be calculated. The deviations for future times are, of course, unknown.

Table 15-1
Mean Annual Air Temperatures and First Harmonic Coefficients Determined for Selected First-Order National Weather Service Stations, for Application to the Air Temperature Representation in the Long-Term Water Temperature Forecast Model

Station	*Mean Annual Air Temperature T, °C (°F)*	*Amplitude a, C° (F°)*	*Phase Angle q*	*Period of Record*
Pittsburgh, Pennsylvania	10.16 (50.29)	12.64 (22.75)	-1.9085	1965-1982
Huntington, West Virginia	12.63 (54.73)	11.66 (20.99)	-1.8734	1965-1982
Covington, Kentucky	11.80 (53.24)	12.84 (23.11)	-1.8866	1965-1982
Louisville, Kentucky	13.39 (56.10)	12.43 (22.37)	-1.8769	1965-1982

d. Model parameters. By substituting Equations 15-1 and 15-3 into Equation 15-2 and integrating to solve for T_w, an equation describing water temperature is derived.* This equation is the basis of the water temperature forecast model. There are two coefficients in this equation, the response coefficient K_r, and the equivalent temperature T_q. The forecast of the water temperature on day j (T_{wj}) is based on information known from the previous day, $j - 1$. The forecast is made in 1-day increments, starting from the date of the forecast. In principle, the forecast can extend indefinitely into the future. However, in practice, the forecasts are limited by the lack of knowledge of future air temperature deviations.

e. Data required for model calibration. The unknown coefficients in the model equation, K_r and T_q, must be determined by analyzing past air temperature records and water temperature records. This suggests the importance of complete and accurate temperature records for forecasting. Generally, the water temperature records are the most difficult to obtain. The unknown coefficients are estimated by a least-squares approach.† The results of calculating the response coefficient and equivalent temperature for six stations on the Ohio River are shown in Table 15-2. In this case separate coefficients have been calculated for two 3-month periods: October through December, and January through March. These two periods cover the entire winter season.

15-4. Model Operation

From the analysis of previous data, the following information is known—air temperature characteristics (mean annual air temperature, first harmonic amplitude, and phase angle), and the water temperature response coefficient and equivalent temperature. From real-time water temperature measurement stations

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* The general equation for T_w, for a specific day j, is given by:

$$\begin{aligned} T_{w_j} &= \bar{T} + a \cos\alpha \sin\left(\frac{2\pi t}{T} + \theta - \alpha\right) \\ &= \left[T_{w_{j-1}} - \bar{T} - a \cos\alpha \sin\left(\frac{2\pi(t-1)}{T} + \theta - \alpha\right)\right] e^{-K_r} \\ &= T_{s_j}\left(1 - e^{-K_r}\right) + T_q\left(1 - e^{-K_r}\right) \end{aligned}$$

where $\alpha = \tan^{-1}(2\pi/K_r T)$.

† The coefficients are estimated by minimizing a function Φ:

$$\Phi = \sum_{j=1}^{n} \left(T_{w_a} - T_w\right)^2$$

where T_{w_a} is the actual water temperature on day j, and T_{w_j} is the water temperature forecast for that day using known values of a, θ, T_{δ_j} and T.

Table 15-2
Sample Model Coefficients for Six Stations on the Upper Ohio River, for Application to Long-Term Water Temperature Forecasts

	Response Coefficient K_r		*Equivalent Temperature* T_q, *C° (F°)*	
Location	*Oct-Dec*	*Jan-Mar*	*Oct-Dec*	*Jan-Mar*
Emsworth L&D*	0.1737	0.0725	1.35 (2.43)	3.45 (6.21)
South Heights, Pennsylvania (ORSANCO)	0.0637	0.0697	1.35 (2.43)	3.45 (6.21)
Montgomery L&D	0.1087	0.0706	1.27 (2.29)	3.52 (6.34)
Hannibal L&D	0.0998	0.0700	0.20 (0.36)	2.95 (5.31)
Racine L&D	0.1000	0.0633	0.20 (0.36)	1.80 (3.24)
Meldahl L&D	0.0596	0.0594	0.20 (0.36)	1.79 (3.22)

* Lock and Dam.

at each location where forecasts are to be made, the actual river water temperatures at the time of the forecast are obtained. The forecasts of air temperature are obtained from the National Weather Service (NWS). Generally, these are represented as deviations from the normal air temperature as described by Equation 15-3. A diagram of the model is shown in Figure 15-1. Generally, the model is run to estimate the period when ice formation is possible, that is, when the water temperature is 0°C (32°F). However, this would not be a conservative estimate because unforecasted deviations in air temperature may cause the water to reach 0°C (32°F) sometime before the actual forecasted date, and often, for a given winter season, 0°C (32°F) may never be reached. Therefore, the following nomenclature has been developed. The term *most-likely ice period* is used to describe the time when the water temperature is forecasted to be 1.5°C (34.7°F) or less. The term *ice watch* is used to describe the time when the water temperature is forecasted to be 0.5 °C (32.9°F) or less.

15-5. Model Results

An example of a sample water temperature forecast is shown in Figure 15-2. This example indicates the location of the forecast, the date of the forecast, the water temperature on the date of the forecast, and the air temperature forecasts provided by the NWS. In this case the NWS forecasts are for normal temperature, that is, the temperature deviations from the temperatures described by Equation 15-3 have been set to zero. Then the example provides the actual forecasted water temperature and a description of the *most-likely ice period* and the *ice watch* period.

15-6. Model Accuracy

To assess the accuracy of the Long-Term Water Temperature Forecast model, the Ohio River Valley Sanitation Commission (ORSANCO) station at South Heights, Pennsylvania, has been used because of its long period of record. There are several ways of assessing the accuracy of the forecast. The first is to determine the mean error of the forecast, that is, the average absolute value of the difference between the forecasted water temperature and the actual. Results of forecasts done on 14 years of records are shown in Figure 15-3. The error is calculated based on the forecast that could be made by assuming that a perfect air temperature forecast is available, that is, by using the actual recorded daily average air temperature. It can be seen that, for the 25-day period following the date of the forecast, the forecasted

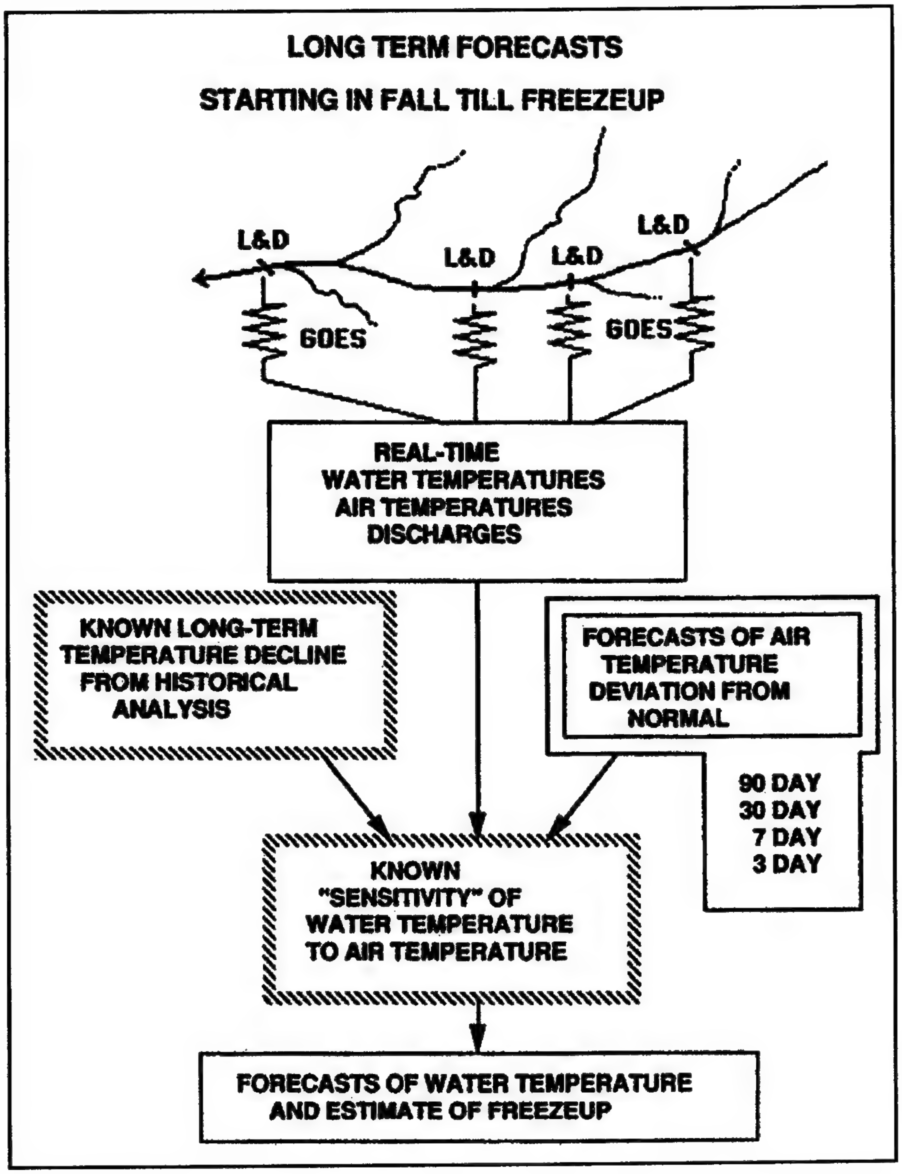


Figure 15-1. Flowchart of long-term water temperature forecast model

water temperatures are more accurate than those determined by simply using the long-term mean water temperature as an estimate.

Section II
Mid-Winter Ice Forecasts

15-7. Objectives

The objectives of the Mid-Winter Ice Forecasts are to provide accurate predictions of the reaches of a river system where ice will be formed, the reaches of a river system where there will be stationary ice

RIM WATER TEMPERATURE FORECAST

SITE: Emsworth Locks and Dam
Ohio River Mile: 6.2

Date of Forecast: 4 October 1987

Water Temperature: 15.0°C (59.0°F)

Air Temperature Forecasts: 3 Day: NORMAL
7 Day: NORMAL
30 Day: NORMAL

DATE	FORECASTED WATER TEMPERATURE °C	°F
01 Nov 87	10.2	50.4
01 Dec 87	4.2	39.6
15 Dec 87	1.9	35.4
01 Jan 88	0.2	32.4
15 Jan 88	0.8	33.4
01 Feb 88	1.0	33.8
15 Feb 88	1.5	34.7

MOST LIKELY ICE PERIOD: 19 Dec 87—15 Feb 87

ICE WATCH: 27 Dec 87—5 Jan 88

Figure 15-2. Typical output information of the long-term water temperature forecast model. *Successive model runs (updates) would yield more precise estimates of the* most-likely ice period *and the* ice watch period

cover, the thickness of the stationary ice cover, the thickness of frazil ice deposited under the ice cover, the water temperature in every reach, and the breakup date of the stationary ice cover. These predictions are to be made as far into the future as possible. However, owing to limitations of weather forecasts, the ice forecasts have a realistic limitation of 5 to 7 days.

15-8. Forecast Model Description

The Mid-Winter Ice Forecast model (Shen 1991)is composed of three submodels and several supporting models. The Mid-Winter Ice Forecast model also has several items that must be specified; these are known as System Parameters. The three submodels are the Hydraulic Model, the Thermal Model, and the Ice Model. Each of these submodels is based on physical principles that will be discussed below. Moreover, each of these submodels has several items that must be entered as input; these are the Physical Parameters and the Initial Conditions. The Initial Conditions define the river system at the time the forecast is made. Each submodel must also be supplied with parameters known as Boundary Conditions; these are not determined by the ice forecast model, but rather are independently forecasted parameters (such as air temperature and tributary discharge) that drive the ice forecast model. The ice forecast model uses the Boundary Conditions to predict new values of the parameters supplied as Initial

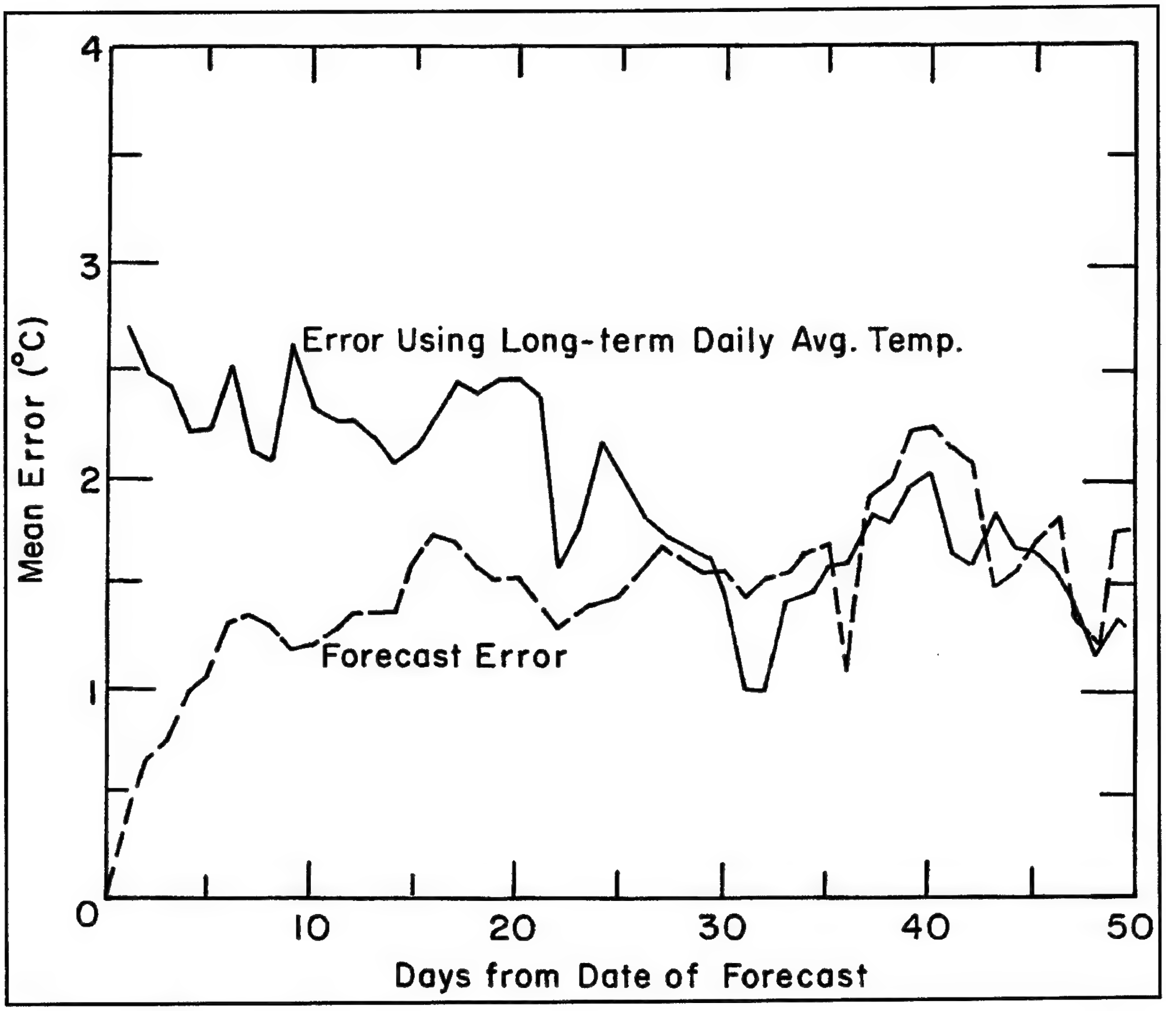


Figure 15-3. Forecast-model accuracy illustrated by plot of error as a function of days since forecast was made. *Forecast naturally has its greatest accuracy immediately following the date of forecast, after which error generally increases with time. For comparison, error resulting from simple long-term daily average water temperatures is also shown and seen to decrease slightly with time. For the period up to about 25 days after a forecast is made, the error in forecasted water temperatures is more acceptable than that associated with reliance on long-term averages.*

Conditions at each time step. These new values are the output of the model, and can serve as the Initial Conditions for the following time step. The output of the model is the forecast of future ice conditions. This is outlined in Figure 15-4. This section consists of a description of the Mid-Winter Ice Forecast model and the required System Parameters, Physical Parameters, Initial Conditions, and Boundary Conditions. This is followed by a discussion of the Model Output of the ice forecast model and a description of the application of the ice forecast model to a river system. The application discussion includes the role of supporting programs to interface the data collection program and generate the Initial Conditions and the Boundary Conditions and also to interpret the Model Output.

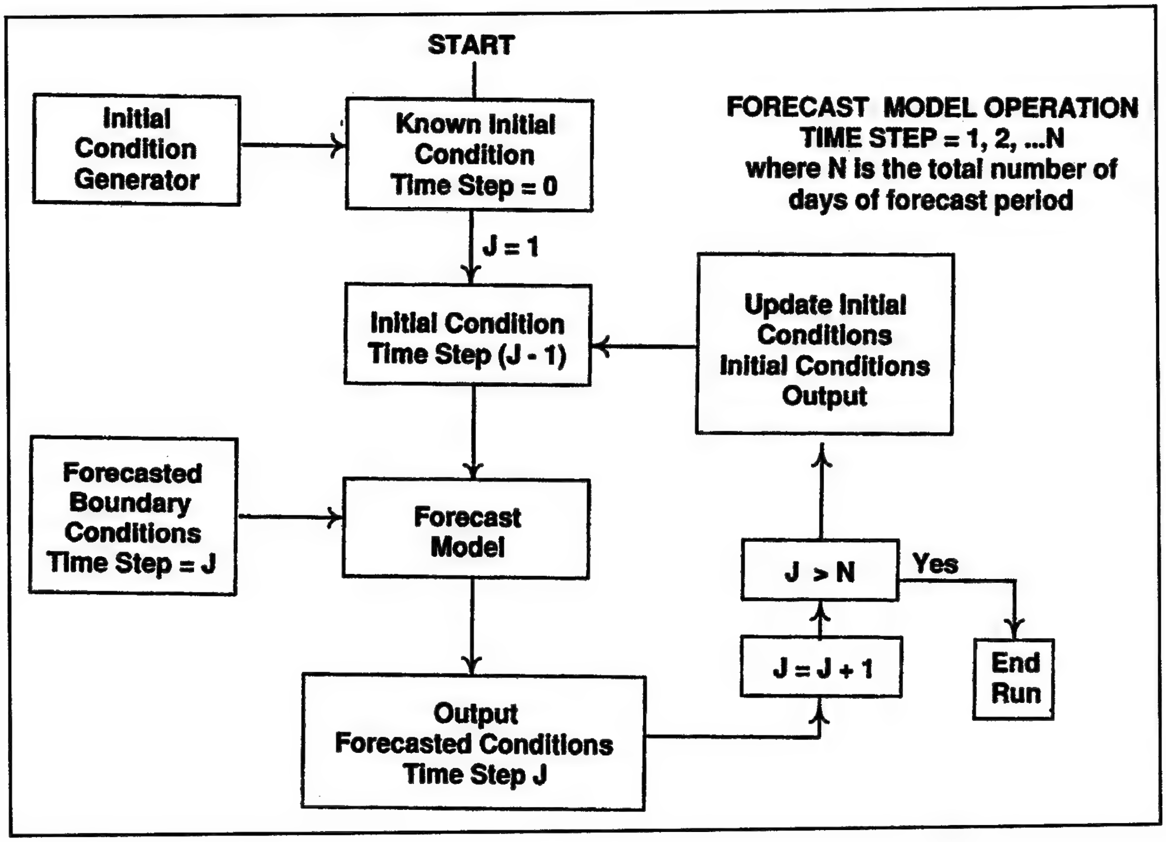


Figure 15-4. Flowchart of mid-winter ice forecast model

15-9. Hydraulic Model Description

The Hydraulic Model used is a one-dimensional, unsteady-flow model. This submodel solves two equations. The first equation is the conservation equation. It assures that the flow entering, leaving, and stored in a reach is balanced. This equation can also consider tributary inflow and other lateral inflow. It may also consider storage of flow in a floodplain. The second equation is termed the momentum equation. This equation assures that the momentum entering and leaving a reach is balanced by the forces acting on that reach. The momentum equation considers the forces of gravity, the channel friction, the hydrostatic pressure, and the possible acceleration of the flow. Both the conservation equation and the momentum equation are one-dimensional, that is, all properties are averaged over any cross section, and the only dimension considered is longitudinal or along the channel.

a. Model equation solutions. Taken together, the conservation and momentum equations are nonlinear, partial differential equations. Therefore, they cannot be solved directly, and they cannot be represented directly in a computer. Generally, they are represented in their finite-difference form and solved at discrete points, termed nodes. The system of nodes is used to represent the river system under consideration. Generally, a node is a point at which information about the channel geometry is known, or for which information is required, such as a lock and dam project. Each node is separated from the next by a distance (the reach length) that can have different values from one node-pair to another. The closer the spacing of nodes is (i.e., the shorter the reach length), the more accurately a river can be represented and the more data that are then required. A river system (a main stem with tributaries) can be represented by

such a system of nodes. It is then necessary to indicate the starting and ending node of each tributary, and the node where the tributary and main stem join. An example of such a system is shown in Figure 15-5.

b. Influence of locks and dams. The Hydraulic Model must also be able to include the effects of locks and dams on the conservation and momentum equations. Generally, for a dam with control gates, this will mean fixing an upper pool or upper gage elevation at a lock and dam if the discharge is below a certain known value. If the discharge exceeds this value, then a rating curve is supplied to determine the upper pool stage. A lock and dam with a fixed crest spillway, for example, has a rating curve to describe its upper pool elevation.

c. Ice effects. The influence of ice must also be taken into account by the Hydraulic Model. The influence of ice will act to reduce the hydraulic radius of a cross section by increasing the wetted perimeter, reduce the cross-sectional area available for flow, and introduce a roughness that will cause an additional friction force that acts on the flow.

d. Hydraulic model output. The principal outputs of the Hydraulic Model are the discharge and the cross-sectional area (from which the depth, velocity, and water-surface top-width are derived) for each node for every time step.

15-10. Thermal Model Description

The Thermal Model computes a heat balance over each river reach. This submodel accounts for heat gained or lost in the reach, and assures that this is reflected in the water temperature response of that reach. However, because of the physical properties of water, it is not possible for the water temperature to decline in any appreciable way below 0°C (32°F). At this point, further heat loss from the water will result in the production of ice, and heat gain will result in the melting of ice. Once all ice in a reach has melted, further heat gain will result in a rise in the water temperature.

a. Heat balance. Generally, the heat transfer to or from river water is dominated by the heat exchange from the open-water surface to the atmosphere. Heat exchange with the channel bed and banks is minor, as is heat gain from friction. Artificial heat sources, such as cooling water discharged from power plants, can be significant and must be included. The presence of an ice cover can greatly reduce the heat exchange with the atmosphere. In this case, the heat transferred through the ice by conduction must be calculated. The presence of an ice cover will allow heat to leave the river water, but not to be gained by the water from the atmosphere. When the ice is greater than about 5 centimeters (2 inches) thick, the heat transfer rate from the water is primarily controlled by the rate at which heat can be conducted through ice.

b. Heat transfer from open water. The heat transfer from an open-water surface to the atmosphere comprises several different modes. These modes include long-wave radiation, short-wave radiation, evaporation, and conduction. It has been found that the daily average heat transfer rate per unit area of open water is represented very well by an equation of the type

$$\phi = h(T_w - T_a)$$

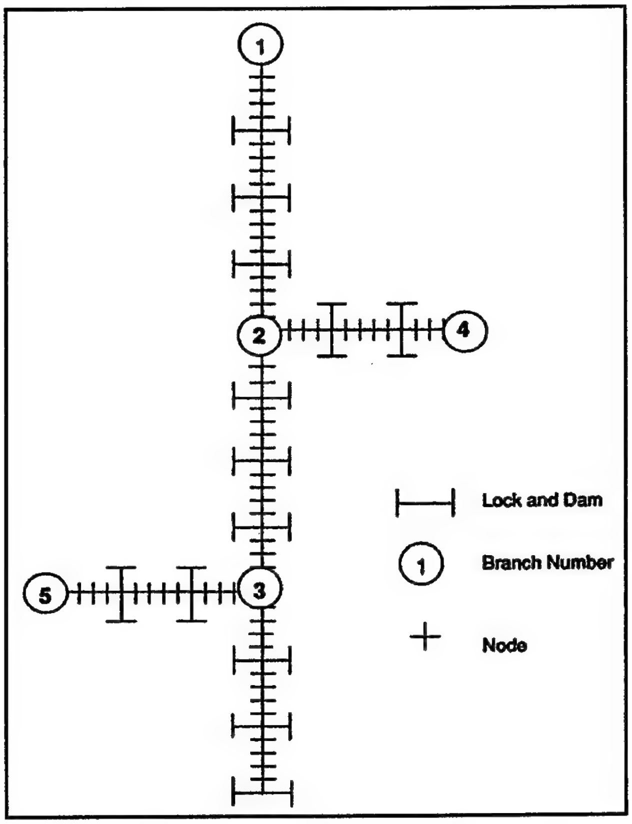


Figure 15-5. River system represented by nodes and branches, for use in the hydraulic model. *Note that nodes exist not only at lock and dam projects and at tributary junctions, but also wherever hydraulic and channel information is known or desired*

where

ϕ = heat transfer rate per unit area

T_w = temperature of the water

T_a = temperature of the air

h = heat transfer coefficient.

The value of the heat transfer coefficient is influenced by the atmospheric stability and wind velocity, but in general can be considered to be a constant for a given region. This equation is of the same form as Equation 15-1. The difference is that here we are considering a specific area or reach of the river, while Equation 15-1 addresses the basin as a whole.

c. Heat transfer through an ice cover. Heat transfer through an ice cover is a balance of the heat lost to the atmosphere, the heat conducted through the ice, and the heat transferred from the water to the bottom of the ice cover. If more heat is transferred to the atmosphere than is transferred from the water to the ice, the ice cover will grow in thickness. If less heat is transferred, the ice cover will melt. The rate of

thickening or melting is determined by the product of the latent heat of fusion of water and the heat transfer rate.

d. Temperature response. The temperature response of a reach of river water is determined by the overall heat loss or gain from the reach, the volume of water contained in that reach, and the heat capacity of the water. The overall heat loss or gain is the product of the heat transfer rate per unit area and the surface area. Both the surface area and volume of a reach are determined by the Hydraulic Model.

e. Initial ice formation. The initial formation of ice in a reach can be quite complex, and the type of ice formed is dependent on the hydraulic conditions in that reach. Generally, the initial ice is in the form of very small disks that are well distributed through the depth of flow; this ice is termed frazil ice. Frazil will tend to collect at the water surface and to move with the general flow velocity. The Thermal Model can calculate the heat loss and calculate the amount of ice formed. However, the formation of a stationary cover ice is determined by the Ice Model (see paragraph 15-11). The presence of open water implies the formation of frazil, and the presence of a stationary ice cover will imply the thickening or melting of that cover.

f. Thermal model output. The output of the Thermal Model is the water temperature at each node for every time step. If the water temperature is at 0°C (32°F), the volume of ice formed or melted will also be calculated. If the reach is open water, the volume of frazil formed will be determined. If the reach is ice covered, the change in thickness will be determined.

15-11. Ice Model Description

Given the hydraulic conditions of stage and velocity (determined by the Hydraulic Model), and the water temperature and volumes of ice formed or melted (determined by the Thermal Model), the Ice Model will then determine where the stationary ice covers are initiated, the manner in which they are formed, their length, their initial thicknesses, and the volume of frazil that is eroded or deposited under them. It is important to note that while the other submodels (the Hydraulic Model and the Thermal Model) are based on general physical principles (that is, the conservation of matter, momentum, and energy), the Ice Model largely reflects principles gleaned through actual observation of the behavior of river ice and the development of empirical relationships.

a. Ice bridging. It is assumed that the initial ice formed on the river is frazil. The frazil particles will rise buoyantly and collect at the water surface to form a slush, which will then flocculate to form pans of ice. It is not possible at this time to calculate what the initial thickness of these pans will be, but a thickness for the initial pans must be entered as a Physical Parameter into the program. Therefore, the initial formation of ice will be in the form of pans whose thickness is a preset parameter. These pans will move with the flow velocity until they reach an obstacle in the flow, or until the concentration of floating ice increases to the point where the ice "bridges" naturally across the stream channel and forms a stationary cover. It is not possible at this time to calculate where these natural bridging points will occur, or under what conditions of flow and ice concentration they will occur. Therefore, the initial bridging locations must be determined through judgment and entered into the program as Physical Parameters. For example, it can be assumed that ice will initially bridge at the locations of locks and dams. Most often, ice bridges at the same locations each winter season. These locations may be at sharp bends, low velocity reaches, etc.

b. Progression by juxtaposition. The initial formation of a stationary ice cover in a reach where an obstacle exists at the downstream end will follow the logic shown in Figure 15-6. This obstacle may be

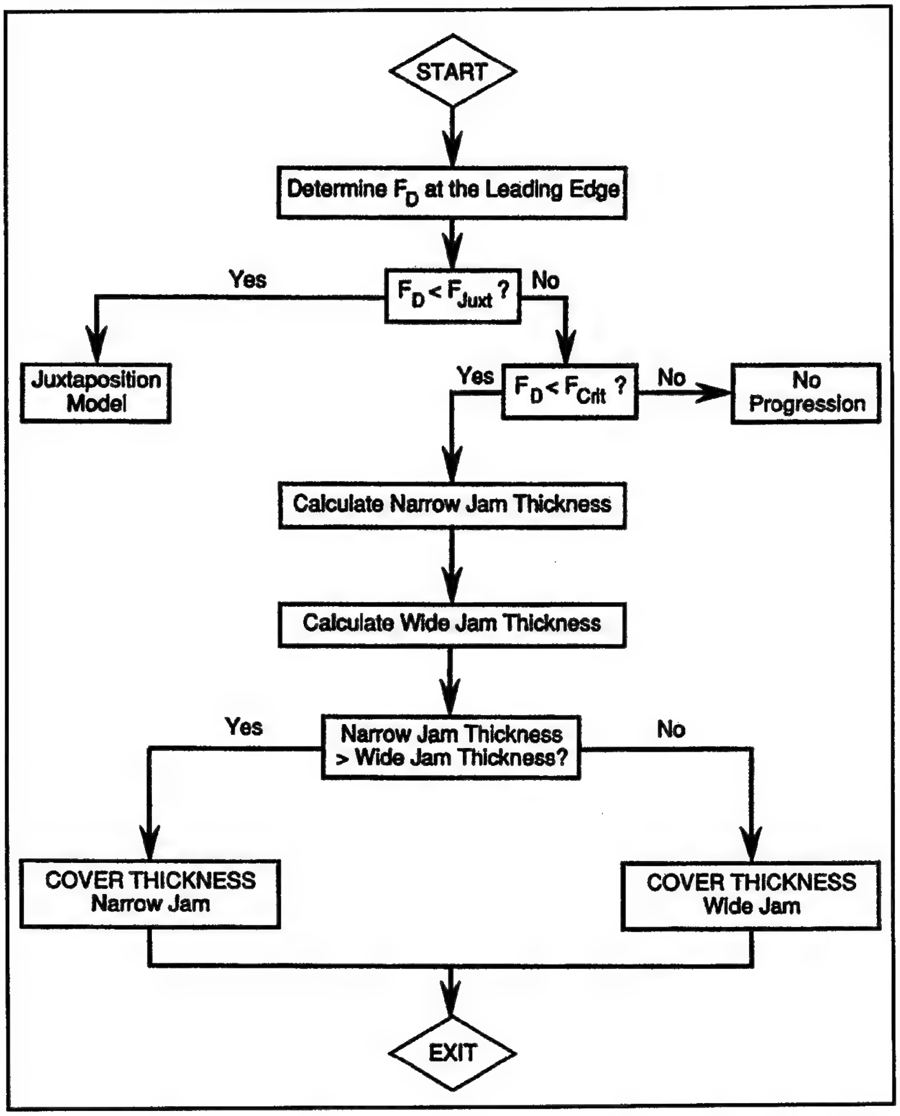


Figure 15-6. Flowchart of the logic used in the ice model. *This flowchart is for determining whether the upstream ice cover progression is by juxtaposition or by jamming (with the associated narrow-jam or wide-jam thickness), or whether there is no progression of the ice cover*

an input ice-bridging location, or the edge of the ice cover that has progressed upstream in the previous time step. The first condition to be addressed is this: Will the ice pans that arrive at the stationary cover remain floating or underturn? If they remain floating, the cover is said to progress by juxtaposition. It is assumed that, if the Froude Number of the flow, defined as

$$F_D = \frac{V}{\sqrt{gD}}$$

where

V = mean velocity

g = acceleration of gravity

D = channel depth

is less than the Juxtaposition Froude Number, then the pans will not underturn and the cover will progress upstream by juxtaposition. The Juxtaposition Froude Number must be entered as a Physical Parameter. It is one of the empirical parameters used in the Ice Model.‡ The rate of ice-cover progression upstream will be determined by the concentration of arriving ice, the velocity of the arriving ice, the thickness of the cover, the porosity of the cover, and the fraction of the total ice flow going into the cover formation. (The porosity of the cover and the fraction of the total ice flow going into the cover are also entered as Physical Parameters.) If, on the other hand, the Froude Number of the flow is greater than the Juxtaposition Froude Number, then the pans will underturn, and may or may not progress upstream. If the pans do progress upstream under this condition, they do so by jamming rather than by juxtaposition.

c. Limit of ice-cover progression. If the Froude Number of the flow exceeds the Juxtaposition Froude Number, it is necessary to check and see if the Froude Number of the flow is greater than a limiting value of the Froude Number for progression. If this is true, no ice-cover progression is possible. All the arriving ice will be swept under the existing ice cover and carried downstream. This means that, until the hydraulic conditions change, the river will remain as ice-free, open-water upstream of this point. This limiting value of the Froude Number for progression is also an empirical value, entered as a Physical Parameter; suggested values are available.

d. Wide and narrow ice jams. If the Froude Number of the flow exceeds the Juxtaposition Froude Number, but is less than the limiting value of the Froude Number for ice-cover progression, then the ice cover can progress in one of two modes. These modes are termed the narrow-jam and wide-jam modes. These modes reflect the balance of forces acting on the ice cover.

(1) In the wide-jam mode, the ice cover must thicken to transfer the forces acting on the cover to the channel banks. The forces acting on the cover are the bottom friction ascribable to the flow and the component of the weight of the cover parallel to the water surface caused by the slope of the water surface. These forces are resisted by the friction of the ice against the channel banks and by any cohesion with the channel banks. It is assumed that the forces acting on the cover are in equilibrium with the resisting force of the channel banks at every point along the channel. The thickness of ice required to provide this equilibrium is termed the equilibrium ice jam thickness, and is calculated assuming that the ice acts as a passive granular material. The Physical Parameters that are required are the underside roughness of the ice cover, the coefficient of friction of the ice with the banks, the coefficient of passive stress for granular ice, the bank cohesion, and the porosity of the ice cover. Once the equilibrium ice jam thickness has been calculated, the progression rate is determined with the same procedure as before.

(2) In the narrow-jam mode, it is assumed that the thickness of the ice cover is determined by the hydraulic conditions at the leading edge of the ice cover. Forces acting on the cover are not a

‡ Suggested values of the Juxtaposition Froude Number are available, or estimates can be made using semi-empirical formulas described by Ashton (1986), where the parameter is termed the "block stability criterion for underturning."

consideration. Specifically, it is necessary that the ice cover be thick enough so that a "no-spill" condition is satisfied. That is, the cover is thick enough to resist the sinkage caused by the acceleration of flow beneath the leading edge of the cover.

(3) Generally, it is not possible to determine beforehand whether an ice cover will progress in the wide-jam or narrow-jam modes. The thickness that will result from each mode is calculated and the mode that results in a greater thickness is used.

e. Conservation of moving ice. The Ice Model balances the concentration of moving ice for each time step. Ice that reaches a stationary ice cover, and does not go into the formation of the ice cover via one of the modes described above, is assumed to be transported under the ice cover. This ice can be deposited under the ice cover, and is considered to be deposited frazil. The deposited ice can then be eroded if the velocity of the water increases sufficiently. The rate of deposition to the underside of the ice cover is determined by a mass balance calculation on the transported ice. The Physical Parameters required are the probability of deposition of an ice particle that reaches the ice/water interface, the buoyant velocity of the frazil particle, and the critical velocity for deposition. If the flow velocity is above the critical velocity for deposition, the frazil will not be deposited. Erosion of the deposited frazil takes place when the local flow velocity under a frazil deposit increases beyond the critical velocity for erosion. The Physical Parameter that is required here is the critical velocity for erosion.

f. Ice-cover stability. After an ice cover has been formed, it can be lost when the forces acting on the cover exceed its ability to transfer these forces to the channel bank. This will happen if the hydraulic conditions change, or if the ice-cover thickness is reduced by melting. Therefore, at each time step, a force balance must be determined on the ice cover in each reach. The friction on the ice cover from the flow and the component of the weight of the cover parallel to the water surface caused by the slope of the water surface are balanced against the ice cover's ability to resist the applied forces. The ice-cover strength is determined by the ice thickness, the coefficient of friction of the ice with the banks, and the bank cohesion. If the force acting on the ice cover exceeds the ability of the ice cover to resist that force, the ice cover is then considered to collapse and become floating and mobile ice.

15-12. System Parameters

System Parameters are data that describe the physical river system that is to be modeled and the manner in which the model is to operate. Generally, these System Parameters do not change their values as the model is run. The following are required System Parameters:

- Number of tributary branches.
- Number and location of nodes.
- Number and location of locks and dams.
- Number of lateral inflows.
- Time step length.
- Total time of model run.

15-13. Physical Parameters

Physical Parameters are data that describe the physical processes that are being modeled. Generally, these are physical constants and do not change their value while the program is being run. These constants are either measured in the field, determined during model calibration, estimated from observation and laboratory experiment, or known from physical principles.

a. Hydraulic Model physical parameters.

(1) Measured in the field:

- Channel geometry of each node.
- Floodplain areas.

(2) Determined from model calibration:

- Channel roughness.
- Contraction and expansion coefficients.

(3) Physical principle: Density of water.

b. Thermal Model physical parameters.

(1) Determined from model calibration:

- Air–water heat transfer coefficient.
- Ice–water heat transfer coefficient.

(2) Physical principles:

- Density of water.
- Heat capacity of water.
- Thermal conductivity of ice.
- Heat capacity of ice.
- Latent heat of fusion of ice.
- Density of ice.

c. Ice Model physical parameters.

(1) Estimated from observation and laboratory experiment:

- Buoyant velocity of frazil particles.
- Probability of ice particle depositing on cover.
- Critical velocity of frazil deposition.
- Critical velocity of frazil erosion.
- Coefficient of passive stress.
- Ratio of longitudinal stress to bank friction.
- Ice–bank cohesion.
- Bridging flag at each node.

- Underside roughness coefficient of ice cover.
- Juxtaposition Froude Number.
- Limiting value of the Froude Number for progression.
- Ice-cover porosity.
- Deposited frazil porosity.
- Initial ice pan thickness.
- Fraction of total ice flow going into the ice-cover formation.

(2) As noted in paragraph 15-11, the Ice Model does not have Physical Parameters based on physical principles nor determined by means of model calibration.

15-14. Initial Conditions

The Initial Conditions are those that describe the physical conditions of the river system at the time that the forecast is made. The following Initial Conditions must be known at each node.

a. Hydraulic Model initial conditions.

- Water surface elevation.
- Discharge.

b. Thermal Model initial condition: Water temperature.

c. Ice model initial conditions.

- Floating ice concentration.
- Ice-cover length.
- Ice-cover thickness.
- Deposited frazil thickness.

15-15. Boundary Conditions

The Boundary Conditions cannot be determined by the Mid-Winter Ice Forecast model. They are the parameters (forecasted by other means) that drive the model. The Boundary Conditions can change with each time step.

a. Hydraulic Model boundary conditions.

- Tributary discharge.
- Lateral inflows.
- Downstream stage.

b. Thermal Model boundary conditions.

- Tributary water temperature.
- Lateral inflow water temperature.
- Air temperature at every node.

c. Ice Model boundary conditions. There are currently no Boundary Conditions to be entered in the Ice Model. However, if known, the ice concentration of the tributaries and lateral inflows could be entered.

15-16. Model Output

The output of the Mid-Winter Ice Forecast model, in general, consists of updated values of the Initial Conditions based on the input Boundary Conditions. Each of the three submodels produces its own output. The output can be specified at each node and at each time step.

a. Hydraulic Model output. The output of the Hydraulic Model consists of the stage and discharge at each node at each time step. The mean velocity can also be calculated since the cross-section geometry is known.

b. Thermal Model output. The output of the Thermal Model consists of the water temperature at each node at each time step.

c. Ice Model output. The output of the Ice Model consists of the following for each node at each time step:

- Concentration of moving ice.
- Presence or absence of an ice cover, and if an ice cover is present, the length and thickness of that ice cover.
- Thickness of deposited frazil.

15-17. Model Calibration

The initial calibration setup of the Mid-Winter Ice Forecast model is not described in detail. However, in general, calibration of the model consists of adjusting the values of the Physical Parameters in each of the submodels so that the Model Output accurately reproduces the observed conditions. This procedure is necessary because in many cases there is no means of actually measuring the required Physical Parameters.

a. Hydraulic Model calibration. Calibration of the Hydraulic Model consists of adjusting the roughness coefficients that determine the resistance of the channel to flow. Generally, the roughness coefficients are adjusted so that, at observed discharges, the corresponding observed water elevations are matched.

b. Thermal Model calibration. Calibration of the Thermal Model consists of adjusting the heat transfer coefficients that determine the heat transfer rates from the water to the air, and from the water to the underside of the ice cover.

c. Ice Model calibration. A telling indication of the uncertain knowledge of river ice is the large number of parameters that could be adjusted during the calibration of an Ice Model. Generally, every Physical Parameter listed under the Ice Model (paragraph 15-13*c*) can be adjusted, as a definite value for each parameter cannot yet be calculated from our understanding of ice physics. Unfortunately, this is not a very satisfactory state of affairs. It is recommended that suggested values of the Physical Parameters be used and not adjusted, unless direct evidence of the need for adjustment is produced.

15-18. Model Operation

A general overview of the operational setup of the Ice Forecasting System is shown in Figure 15-7. The system may be divided into four general components: Data Collection and Transmission, Data Reduction and Data Base Management, Initial Conditions and Boundary Conditions Generators, and the Mid-Winter Ice Forecast model itself.

a. Field data collection and transmission. Data collected and transmitted for the model at present are water temperature, air temperature, and water-surface stage. This information is collected by Data Collection Platforms (DCPs) and transmitted via Geostationary Observational Environmental Satellite (GOES) to a down-link at a central location. The equipment and setup of a DCP with the appropriate sensors are addressed in Chapter 16. Thermistors, which change resistance in response to temperature change, are used to measure temperature. As DCPs can generally only measure voltages, a voltage divider circuit must be used to convert the thermistor resistance to a voltage that can be measured by the DCP. Generally, the following data must be transmitted to accurately determine temperature—the measured voltage across the voltage divider circuit, the measured voltage across the thermistor, and a measurement of the voltage across a reference resistor. The last measurement is necessary to correct for any impedance mismatch.

b. Data reduction and data base management. The transmissions from the DCPs are coded, and these coded transmissions must be decoded and converted to the proper engineering units. To determine temperature accurately from thermistor measurements, the actual thermistor resistance must be determined (based on the transmitted voltages), the resistance must be corrected for any impedance mismatch, and then the thermistor matched up with the proper calibration constants to convert the thermistor resistance to a temperature. A program (DCP.FOR) was developed for this purpose. DCP.FOR has a highly flexible structure for describing a particular DCP site, and this description can easily be modified or updated. This is particularly important during the setup of large data collection networks, when sensors may often be moved, recalibrated, or replaced. DCP.FOR can also decode the messages from any other meteorological sensor that has a linear output. DCP.FOR creates an output file whose format is fixed, but allows any arrangement of sensors as input to the DCP. A single file is created for each station for each month. The measured value of each sensor, in engineering units, is stored in a fixed format in the file. This allows a flexibility in the sensor configuration at the DCP, while maintaining a data base whose format is fixed. The output file of DCP.FOR has been interfaced with the Corps DSS data base system.

c. Initial Conditions and Boundary Conditions Generators. These are programs that take the actual field data and the forecasted values of air temperature and tributary discharge to create the proper Initial Conditions file and Boundary Conditions file for the Mid-Winter Ice Forecast model. These are discussed in more detail in paragraphs 15-20 and 15-21.

d. Mid-Winter Ice Forecast Model. The Mid-Winter Ice Forecast model was discussed previously. The model (using the Initial Conditions and the Boundary Conditions created by the Initial Conditions and Boundary Conditions Generators) prepares the forecast of predicted ice conditions. Two different modes of operation will be described: the Update Mode and the Forecast Mode (see Paragraph 15-22).

15-19. Location of Field Measurement Sites

Ideally, a field measurement site could be located at each node of the model. The site would provide information on the water stage, discharge, air temperature, and water temperature. However, this would be prohibitively expensive, and the amount of data generated would quickly bury any practical data

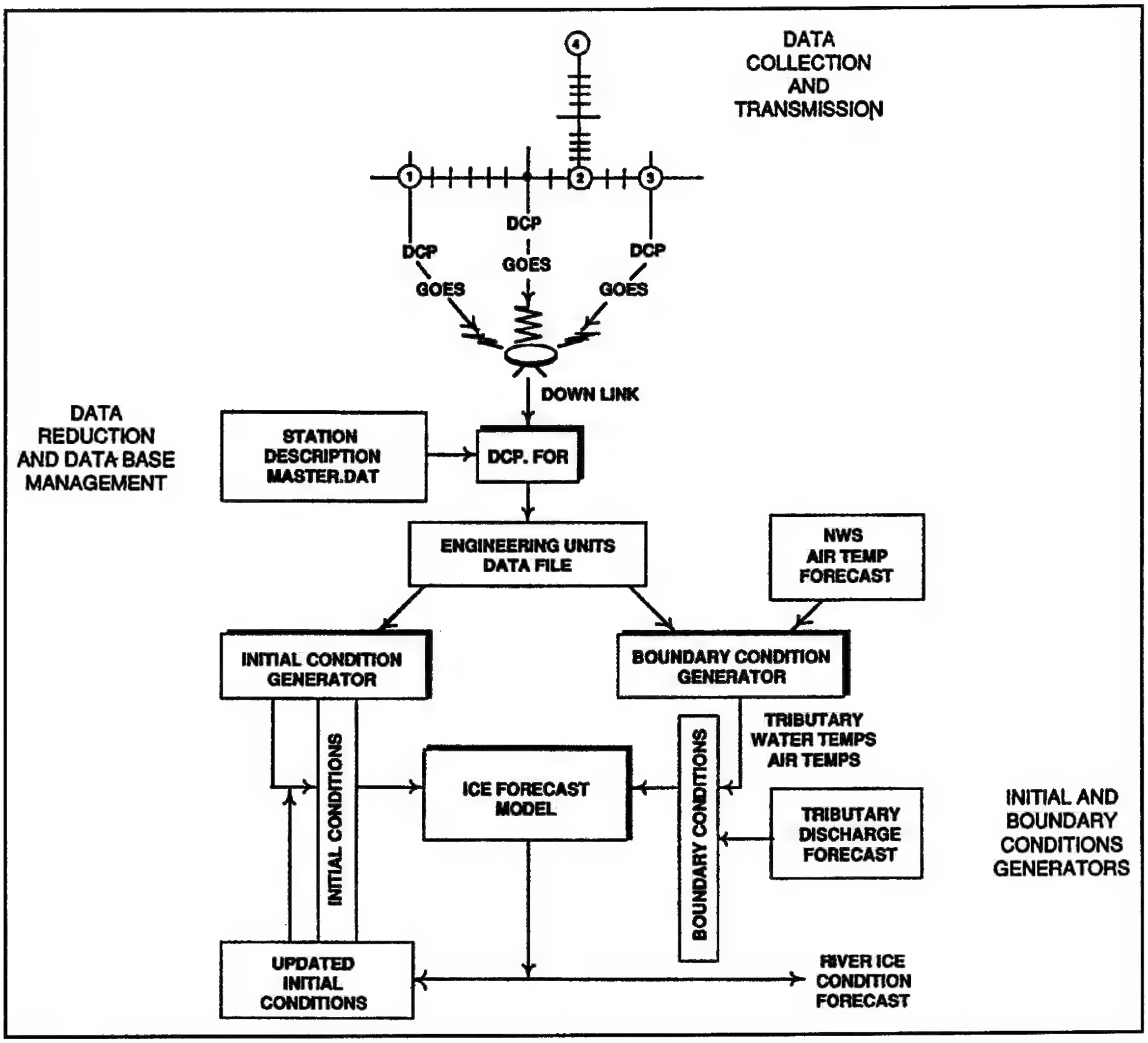


Figure 15-7. Overall flowchart of the ice forecasting system. *Within the Ice Forecasting System, the Mid-Winter Ice Forecast model operates under the support of Data Collection and Transmission, Data Reduction and Data Base Management, and Initial Conditions and Boundary Conditions Generators (DCP.FOR and MASTER.DAT are computer program names)*

management scheme. In fact, field measurement sites should be kept to a minimum and located where they will provide the optimum information to allow the most accurate creation of the Initial Conditions and Boundary Conditions as input to the Mid-Winter Ice Forecast model. In general, the following guidelines apply:

- Field sites to measure water temperature should be located at the upstream end of the main stem and at the upstream end of each tributary to be modeled.

- Field sites to measure air and water temperature should be located throughout the river system to be modeled, and in sufficient density to provide a representative "picture" of the actual conditions. To determine this, some background study will be required to understand the meteorological and climatological conditions of the river system to be modeled. For example, on the Ohio River, field

sites were located at an average spacing of about 130 kilometers (about 80 miles) along the river. However, in the upstream reaches of the Ohio River, where the winter climate varied over rather short distances, the stations were much closer. A good indication of climatic variation can be seen on a map indicating average freezing degree-days for a given winter month; January is the best month to represent this variation.

- A field site should be located at the downstream end of the river system that is modeled.

15-20. Initial Conditions Generator

The Initial Conditions required in the model are listed in paragraph 15-14.

a. Hydraulic Model. The generation of Initial Conditions for the Hydraulic Model is not discussed in detail here. It can be assumed that the Initial Conditions of stage and discharge are available from a previous model run (Update Mode), from a steady-state backwater measurement, or from physical measurement with interpolation.

b. Thermal Model. The Initial Condition of water temperature for the Thermal Model at each node can be determined from a previous model run (Update Mode) or from the reported measurements from the field sites. To determine the water temperature at each node from the field sites, the procedure is to first determine the average water temperature at each site for the previous 24 hours. Then, for the main stem, linearly interpolate the water temperature at each node between the field sites. For the tributaries, linearly interpolate the water temperature between the site at the upstream end of the modeled tributary section and the temperature calculated in the previous step for the main stem at the confluence of the tributary and the main stem. If no upstream site is available, a reasonable approximation is to use the temperature of the main stem at the confluence as the temperature for the entire reach of the modeled tributary.

c. Ice Model. The Initial Conditions for the Ice Model are the floating ice concentration, ice-cover length and thickness, and thickness of deposited frazil. It is not possible to physically measure the concentration of floating ice, although it can be visually estimated by experienced personnel during overflights. The ice-cover length can also be estimated from visual observation, preferably by aerial videotaping of the entire reach to be modeled, as described in Chapter 16. Generally, the solid ice cover and frazil thicknesses are not available, except at a very few locations. With the Ice Model data so scarce and incomplete, the realistic alternative is to generate the initial ice conditions from previous model runs (Update Mode).

15-21. Boundary Conditions Generator

The Boundary Conditions required are listed in paragraph 15-15. The Boundary Conditions are independently forecasted parameters that drive the model. Generally, the Boundary Conditions can change with every time step. Inaccurate forecasts of future Boundary Conditions will produce inaccurate model results.

a. Hydraulic Model. The generation of Boundary Conditions for the Hydraulic Model is not discussed in detail here. The forecasts of tributary and lateral discharges and downstream stage can be determined by a variety of means.

b. Thermal Model. The principal Boundary Condition of the Mid-Winter Ice Forecast model is the air temperature Boundary Condition of the Thermal Model. Generally, the daily average air temperature is used as the Boundary Condition. Forecasts of maximum and minimum air temperature are available from

the NWS. A good estimate of the daily average is the mean of the maximum and minimum. Forecasts of the air temperature will undoubtedly be available at several locations throughout the river system where the Mid-Winter Ice Forecast model is to be used. A linear interpolation between the air temperature forecast locations is used to determine the air temperature Boundary Condition at each node.

(1) The forecasts of the tributary water temperature are made using the total watershed approach that is employed in making the Long-Term Water Temperature Forecasts, described in Section I. Information that is required includes the response coefficient and the equivalent water temperature, the actual water temperature on the day the forecast is made, and the forecasted air temperatures. With this information, based on the total watershed approach, a forecast of the tributary water temperature Boundary Condition can be made.

(2) The forecasts of the lateral inflow water temperature can be used to include the influence of artificially heated discharge from power plants, etc. Generally, the lateral inflow water temperatures will not be a factor, as these will be very near or at the main stem water temperature. For locations where heated discharges may be important, the lateral inflow water temperature can be put at a set value above the nearest forecasted tributary water temperature, representing the heat added by a power plant or industrial facility.

c. Ice Model. There are generally no forecasts of ice conditions suitable for use as forecasted Boundary Conditions of the Ice Model. If an ice run is expected on a tributary, this could be used as a Boundary Condition as long as the ice concentration can be estimated.

15-22. Modes of Operation

The Mid-Winter Ice Forecast model can be operated in two modes, a Forecast Mode and an Update Mode. The Forecast Mode starts with the existing Initial Conditions and uses forecasted values of the Boundary Conditions to produce the Model Output. The Update Mode starts with the Initial Conditions that existed the last time the model was run. If the model is operated daily, for example, the Initial Conditions are those existing on the previous day. The actual values of the Boundary Conditions, measured at the field sites, are then used to produce the Model Output. In this way the previous existing conditions are updated to reflect the present existing conditions. Generally, the model is run twice on any day a forecast is made, once to update the Initial Conditions and once to forecast the future ice conditions.

15-23. Model Results

A sample of the Model Output over an entire winter season is shown graphically in Figure 15-8. In this simulation, actual recorded air temperatures and tributary discharges were used. The ice bridging locations were chosen to be at each lock and dam, consistent with observation. The simulation is for the Upper Ohio River, and the location of each lock and dam is indicated. The period covered by the simulation in Figure 15-8 is from 22 December 1985 through 12 February 1986, and the presence of ice is shown as determined by the model. In Figure 15-9, a sample 5-day forecast is shown, also for the Upper Ohio River. This forecast was prepared based on forecasted air temperatures and the actual Initial Conditions on the day that the forecast was made.

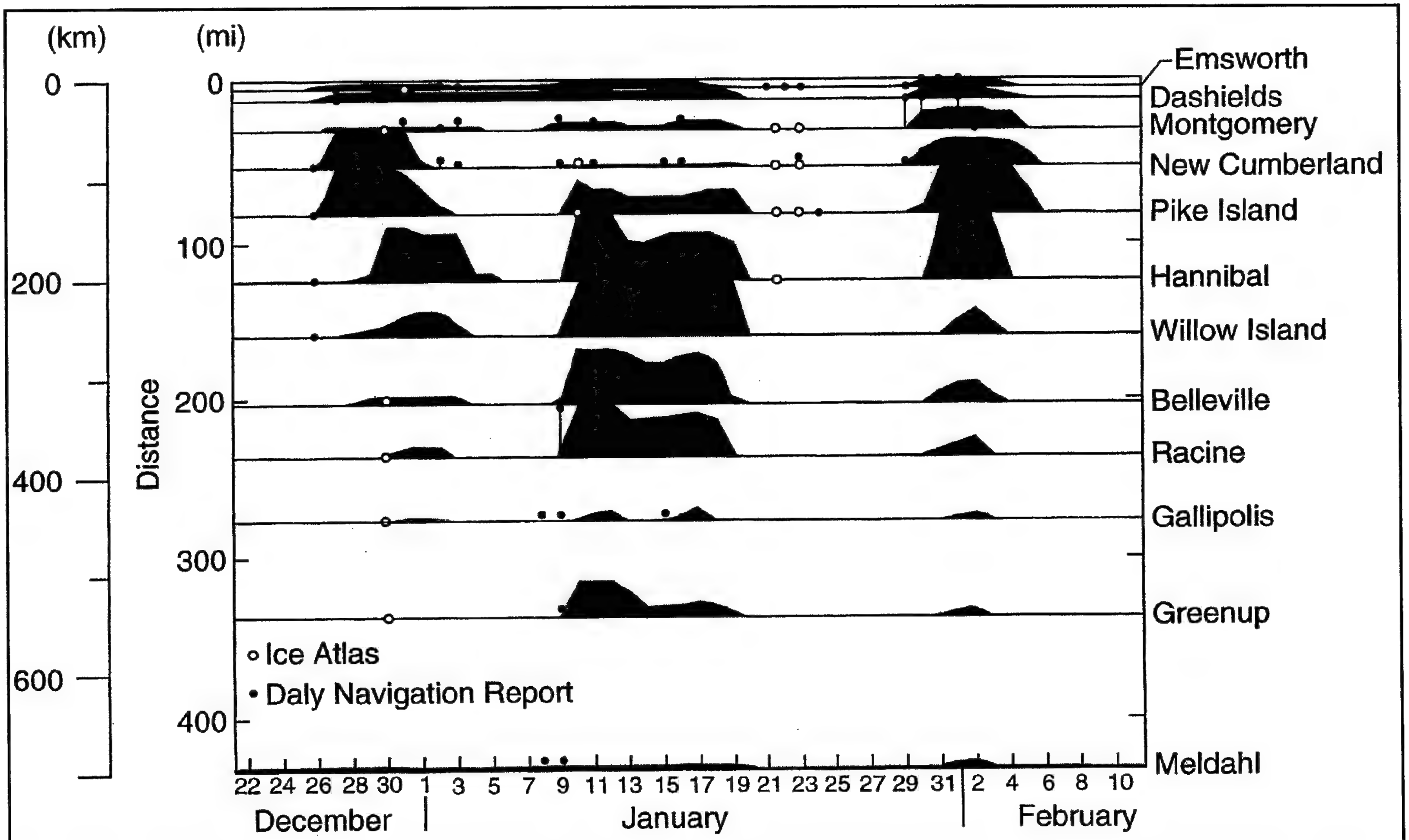


Figure 15-8. Portrayal of the output of the Ice Forecasting System for the Upper Ohio River during the 1985-86 winter. *The shaded areas indicate forecasted ice cover on the river; elsewhere the river was forecasted to be open. Choosing a river location on the diagram and moving across the diagram horizontally gives a time-based summary of the sequence of forecasted ice cover throughout the winter for that location. Similarly, choosing a date during the winter and moving vertically up or down the diagram gives a location-based summary of forecasted ice cover for the Upper Ohio on that particular date. Shown for comparison is ice coverage information based on daily navigation reports issued by the Pittsburgh and Huntington Districts, and an ice atlas (Gatto et al. 1987) based on aerial videotapes*

ICE COVER CONDITIONS ON 12-20-89

DAM	LENGTH MILES	ICE THICKNESS FEET	PER CENT OF POOL WITH ICE	WATER TEMP DEG F	AIR TEMP DEG F
EMSWORTH	0.00	0.00	0	32.70	14.00
DASHIELD	2.96	0.18	44	32.00	14.00
M-GOMERY	0.00	0.00	0	33.37	14.00
NEW CUM	15.20	0.24	79	32.00	14.07
PIKE IS	29.70	0.16	100	32.00	14.18
HANNIBAL	0.30	0.00	5	32.00	14.32
WILL IS	0.47	0.00	10	32.00	14.43
BELVILLE	0.00	0.00	0	32.23	14.56
RACINE	0.00	0.00	0	32.18	14.67
GLPOLLIS	0.00	0.00	0	32.70	14.74
GREENUP	0.00	0.00	0	33.26	14.85
MELDAHL	0.00	0.00	0	35.20	15.01

ICE COVER CONDITIONS ON 12-21-89

DAM	LENGTH MILES	ICE THICKNESS FEET	PER CENT OF POOL WITH ICE	WATER TEMP DEG F	AIR TEMP DEG F
EMSWORTH	0.00	0.00	0	32.88	8.01
DASHIELD	2.96	0.36	44	32.05	8.01
M-GOMERY	0.00	0.00	0	33.37	8.01
NEW CUM	15.20	0.34	79	32.07	8.40
PIKE IS	29.70	0.43	100	32.00	8.91
HANNIBAL	42.30	0.17	100	32.00	9.64
WILL IS	35.30	0.22	100	32.00	10.18
BELVILLE	41.20	0.12	100	32.00	10.83
RACINE	33.60	0.09	100	32.00	11.35
GLPOLLIS	1.89	0.00	22	32.00	11.70
GREENUP	3.64	0.00	74	32.00	12.20
MELDAHL	0.00	0.00	0	34.07	12.99

ICE COVER CONDITIONS ON 12-22-89

DAM	LENGTH MILES	ICE THICKNESS FEET	PER CENT OF POOL WITH ICE	WATER TEMP DEG F	AIR TEMP DEG F
EMSWORTH	1.73	0.00	43	32.00	1.00
DASHIELD	3.56	0.44	53	32.00	1.00
M-GOMERY	0.00	0.00	0	32.05	1.00
NEW CUM	15.20	0.42	79	32.31	1.40
PIKE IS	29.70	0.61	100	32.00	1.90
HANNIBAL	42.30	0.50	100	32.00	2.64
WILL IS	35.30	0.51	100	32.00	3.18
BELVILLE	41.20	0.44	100	32.00	3.83
RACINE	33.60	0.39	100	32.00	4.35
GLPOLLIS	40.70	0.30	100	32.00	4.69
GREENUP	60.80	0.31	100	32.00	5.22
MELDAHL	0.00	0.00	0	32.76	6.01

Figure 15-9. Typical output information from the Mid-Winter Ice Forecast model. *This output covers a 5-day period on the Upper Ohio River*

ICE COVER CONDITIONS ON 12-23-89

DAM	LENGTH MILES	ICE THICKNESS FEET	PER CENT OF POOL WITH ICE	WATER TEMP DEG F	AIR TEMP DEG F
EMSWORTH	6.00	0.48	100	32.00	-0.99
DASHIELD	7.10	0.55	100	32.00	-0.99
M-GOMERY	18.40	0.41	100	32.00	-0.99
NEW CUM	22.70	0.46	100	32.00	-0.44
PIKE IS	29.70	0.72	100	32.00	0.28
HANNIBAL	42.30	0.80	100	32.00	1.31
WILL IS	35.30	0.77	100	32.00	2.07
BELVILLE	41.20	0.74	100	32.00	2.97
RACINE	33.60	0.70	100	32.00	3.69
GLPOLLIS	40.70	0.64	100	32.00	4.17
GREENUP	60.80	0.64	100	32.00	4.89
MELDAHL	94.20	0.12	100	32.00	6.01

ICE COVER CONDITIONS ON 12-24-89

DAM	LENGTH MILES	ICE THICKNESS FEET	PER CENT OF POOL WITH ICE	WATER TEMP DEG F	AIR TEMP DEG F
EMSWORTH	6.00	0.81	100	32.00	0.00
DASHIELD	7.10	0.87	100	32.00	0.00
M-GOMERY	18.40	0.76	100	32.00	0.00
NEW CUM	22.70	0.80	100	32.00	0.46
PIKE IS	29.70	0.83	100	32.04	1.09
HANNIBAL	42.30	0.98	100	32.00	1.98
WILL IS	35.30	0.98	100	32.00	2.62
BELVILLE	41.20	0.98	100	32.00	3.42
RACINE	33.60	0.94	100	32.00	4.03
GLPOLLIS	40.70	0.89	100	32.00	4.44
GREENUP	60.80	0.88	100	32.00	5.05
MELDAHL	94.20	0.50	100	32.00	6.01

Figure 15-9. (Concluded)

15-24. References

a. Required publications.
None.

b. Related publications.

Ashton 1986
Ashton, G.D., ed. 1986. *River and Lake Ice Engineering*, Water Resources Publications, Littleton, Colorado.

Gatto et al. 1987
Gatto, L.W., S.F. Daly, and K.L. Carey 1987. *Ice Atlas, 1985-1986: Monongahela River, Allegheny River, Ohio River, Illinois River, Kankakee River*, Special Report 87-20, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Shen et al. 1991
Shen, H.T., G. Bjedov, S.F. Daly, and A.M. Wasantha Lal. 1991. *Numerical Model for Forecasting Ice Conditions on the Ohio River*, CRREL Report 91-16, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Chapter 16
Ice-Related Hydrometeorological Data Collection and Monitoring

16-1. Introduction

Effective regulation of Corps water control and navigation projects requires the collection of a wide variety of real-time hydrometeorological data from field sites. There are reporting stations at each lock and dam. The data can be manually obtained by the lock and dam staff, or can be obtained using Data Collection Platforms (DCPs) via the GOES (Geostationary Observational Environmental Satellite) near real-time data collection system. (GOES is operated by the National Oceanic and Atmospheric Administration [NOAA].) Downlinks are in operation throughout the northern latitudes at the New England District, the Ohio River Regional Headquarters of the Great Lakes and Ohio River Division, the Rock Island District, and the Missouri River Regional Headquarters and North Pacific Regional Headquarters of the Northwestern Division. These downlinks enable each Division and District to collect data from field sites at intervals of 4 to 24 hours. The data are checked for completeness before they are stored in dedicated water control computers and are available for analysis by all Corps personnel. ER 1110-2-248 provides for Corps policy when using the GOES data collection system. Ice conditions can also be monitored using aircraft and satellites; video and still photographs are often used to track ice conditions along navigable waterways. A schematic of a systems approach to data collection and distribution is shown in Figure 16-1.

Section I
Numerical Data

16-2. Near Real-Time Data Collection

Ice information can be obtained in near real-time using the GOES data collection system. Each Corps office, per ER 1110-2-249, has a Water Control Data System (WCDS) that meets the requirements of automated near real-time data collection, processing, and dissemination for making near real-time water control decisions. A GOES data collection system is made up of four parts: the DCP with related sensors, the GOES satellite, the direct ground readout station, and the WCDS. Authorization to use the GOES system is required, and software for processing and dissemination of ice information is necessary for the use of this system in a river ice management scheme.

16-3. DCP System

The instrumentation requirements for ice monitoring, as in any engineering study, are defined by the kind and accuracy of measurements required and the frequency of data collection necessary. Existing ice forecasting models use the temperature-index approach to predict the onset and breakup of river ice.

a. Temperature-index approach. The temperature-index approach requires water temperature and air temperature data. These are the minimum requirements for an ice monitoring station. This information, in the absence of a forecast model, could be used by the lockmaster to determine operating criteria. The other extreme would be using an energy-balance model to forecast ice conditions. The energy-balance approach would require other hydrometeorological data in addition to water and air temperatures, such as wind speed and direction, solar radiation, and river stage. Table 16-1 shows the parameters to be measured at both the temperature-index and energy-balance types of stations, as well as their resolution and accuracy requirements. The DCP and sensors selected should have the capability to

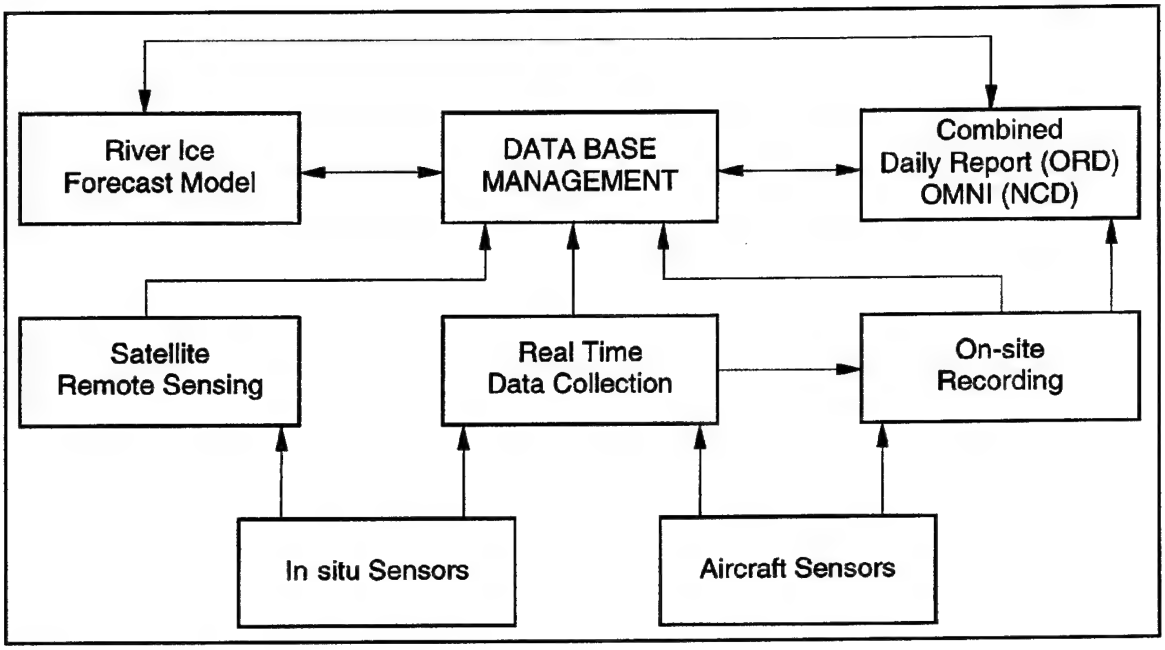


Figure 16-1. Schematic of data collection system for ice information

Table 16-1
Parameters for Ice-monitoring DCP Sites

Parameter	Resolution	Accuracy
Water temperature	0.1 °C (0.2 °F)	±0.1 °C (±0.2 °F)
Air temperature	0.5 °C (1 °F)	±0.5 °C (±1 °F)
Wind speed	0.3 m/s (1 ft/s)	±5%
Wind direction	10°	±5°
Solar radiation	10 W/m^2 (1 W/ft^2)	±10 W/m^2 (±1 W/ft^2)
Barometric pressure	3 mb (0.1 in. Hg)	±3 mb (±0.1 in. Hg)
Relative humidity	5%	±5%
Precipitation	0.2 mm (0.01 in.)	±0.2 mm (±0.01 in.)
River stage	0.003 m (0.01 ft)	±0.003 m (±0.01 ft)
Dam gate setting	0.15 m (0.5 ft)	±0.15 m (±0.5 ft)
Ice thickness	0.03 m (0.1 ft)	±0.03 m (±0.1 ft)

supply the given resolution and accuracy. The need for high resolution and accuracy in water temperature measurement cannot be overemphasized, particularly when such data are inputs to an Ice Forecasting System.

b. Average daily temperature. Normally, for the temperature-index approach to ice forecasting, a daily average air temperature and a daily average water temperature are used. To best calculate a daily average of these values, data should be collected every hour. This also holds for the energy-balance approach. Based on the amount of data to be transmitted, a 4-hour transmission interval is best.

16-4. Water Temperature Measurements

A system developed for remote, accurate river water temperature measurements can be installed at any facility where a water-temperature probe can be properly mounted in contact with the flowing river water. The data can be recorded on a data logger or transmitted by a DCP through the GOES system. Described below are the water temperature measurement system itself and the method of installing it, interfacing the system with a DCP or data logger for recording the water temperature measurements, and reducing the information to engineering units.

a. Description. This water temperature measurement system consists of a water-temperature probe, a probe support pipe with probe adaptor, connecting cable, and a data logger or DCP (Figure 16-2). If a DCP is used, a special interface is needed for the probe.

b. Water-temperature probe. The water-temperature probe is a 0.9-meter (3-foot) length of stainless steel tube with an 2.5-centimeter (1-inch) outside diameter (Figure 16-3). The lower tip of the probe is nylon and contains three thermistors. A cable grip attaches the water-temperature probe to the cable at its upper end. The water-temperature probe is deployed by dropping it down the probe support pipe and seating it in the probe adaptor. The probe is designed both to protect the thermistors from being hit by debris while allowing them to directly contact the water and to be conveniently removable for repair or replacement. The cable connected to the water-temperature probe does two jobs: it provides electrical connection to the thermistor, and it is used to place or remove the probe by hand.

c. Thermistors. The thermistors in the probe are typically of the bead-in-glass type and are suitable for immersion in water. The thermistors are individually spliced into the cable. Each splice must be individually tested for electrical and mechanical integrity and to make sure that it is waterproof. A strain relief device attached to the nylon tip prevents any strain from being applied directly to the thermistors. Depending on the application, the thermistors can be calibrated individually or as a group.

d. Probe support pipe and probe adaptor. The probe support pipe protects the probe from debris or ice, holds the probe, and provides an easy way for the probe to be installed and removed. At the lower end of the probe support pipe is the probe adaptor (Figure 16-2). The adaptor has one Teflon or nylon ring that cradles the probe and holds it in position (Figure 16-3). The probe support pipe is 3.2-centimeter (1-1/4-inch) schedule 80 galvanized steel pipe with couplings. Installation of the probe support pipe and adaptor is discussed in subparagraph 16-4*i*(1) below.

e. Connector box. At the upper end of the probe support pipe is a connector box (Figure 16-4) that provides easy access for placing or removing the water-temperature probe. A water-resistant electrical connector attaches the cable to the water-temperature probe and the cable to the data logger or DCP. The connector box is typically a 3.2-centimeter (1-1/4-inch) Line Back (LB) conduit box (zinc electroplate with aluminum lacquer), with a water-resistant neoprene-gasketted cover, and bushings to connect with the probe support pipe and conduit.

f. Conduit. A 1.9-centimeter (3/4-inch) conduit protects the cable running from the connector box to the location of the DCP or data logger. In many instances existing cableways can be used. If new conduit is installed, provision for pull boxes at appropriate intervals must be made.

g. Cable. The cable used to connect the temperature probe and the electrical connector in the connector box must be rugged. A petrolatum-polyethylene gel-filled cable with a polyethylene jacket is recommended. The cable should have a solid copper tape shield with three-pair 19-AWG conductors.

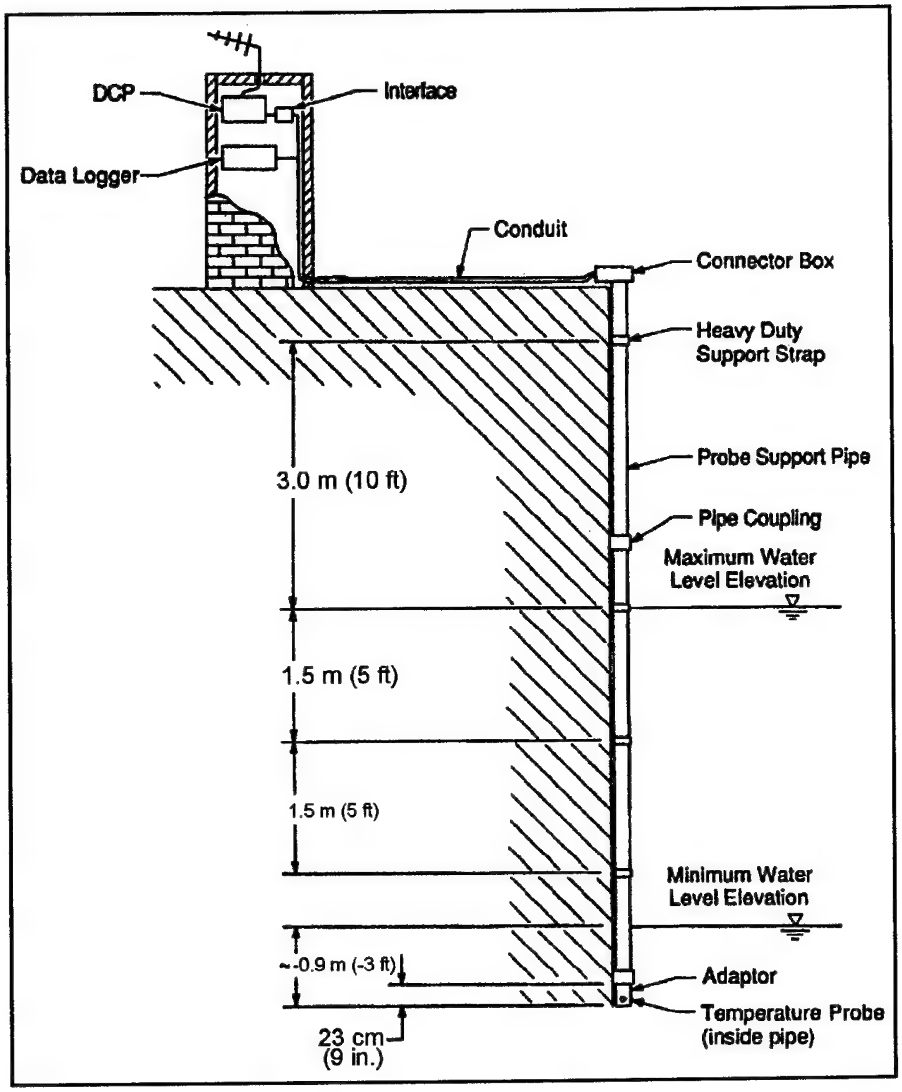


Figure 16-2. Water-temperature measurement system

This type of cable is relatively inexpensive and will provide long life. The cable is stiff and can be used only for straight runs or wide sweeps. A wire cable support grip may be attached to the upper end of the cable to assist in placing or removing the water-temperature probe. To hook up the electrical connectors in the connector box and the interface box, a cable with three 18-AWG, twisted, shielded pairs with drain wire is recommended. The cable should have a polyvinyl chloride (PVC) outer jacket. This type of cable is more flexible than the gel-filled cable and can easily be pulled through the recommended conduit. This cable has also been used to connect the temperature probe and the electrical connector in the connector box with success.

h. DCP Interface. Generally, a DCP can measure only voltages. Thermistors, however, change resistance in response to changing temperature. The DCP interface, therefore, is a simple voltage divider circuit that converts the thermistor resistance to a voltage. The interface is a rectangular box, 5.7 × 5.7 × 12.7 centimeters (2-1/4 × 2-1/4 × 5 inches), that is typically installed immediately adjacent to the DCP.

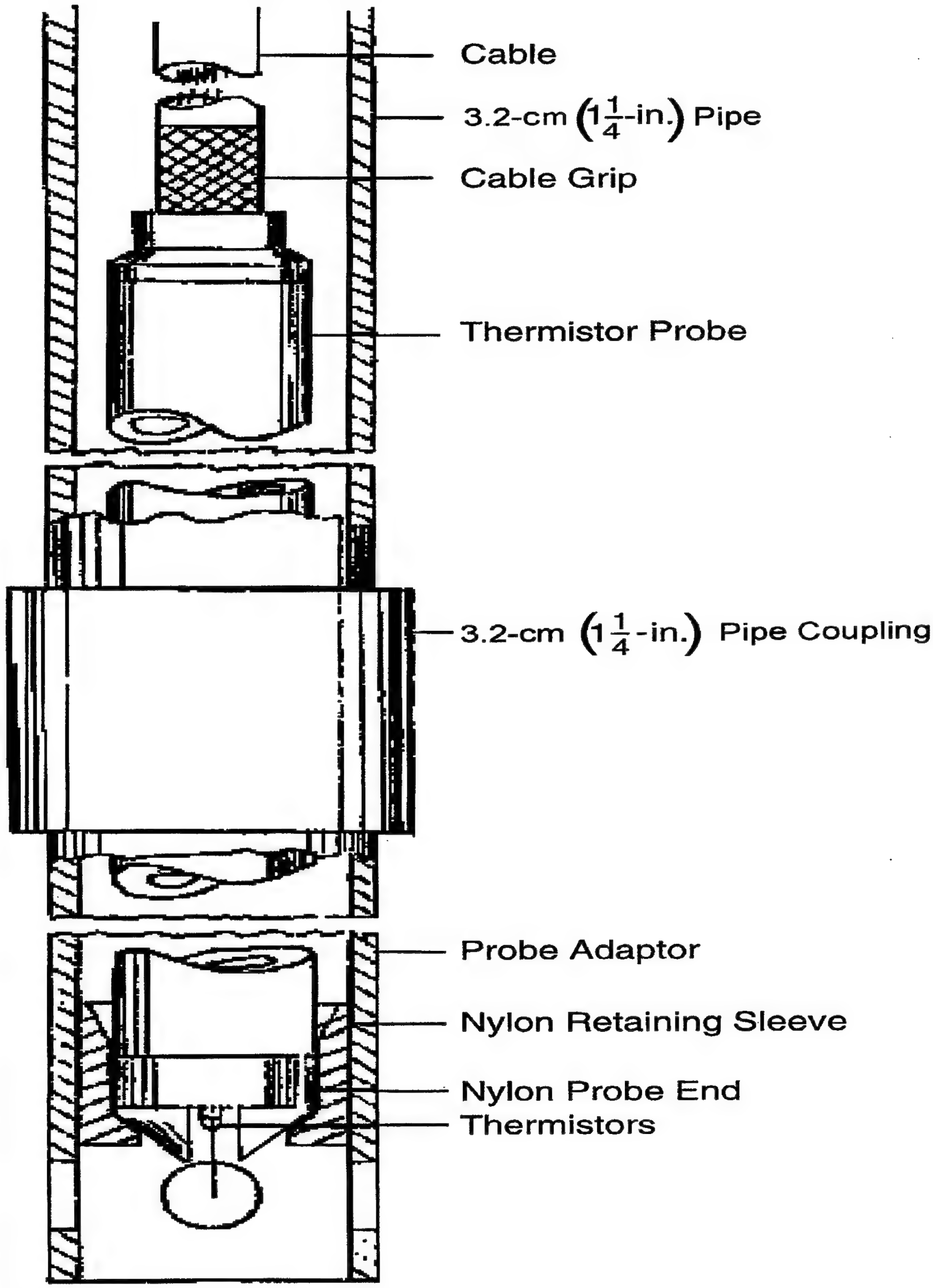


Figure 16-3. Water-temperature probe within the probe adaptor

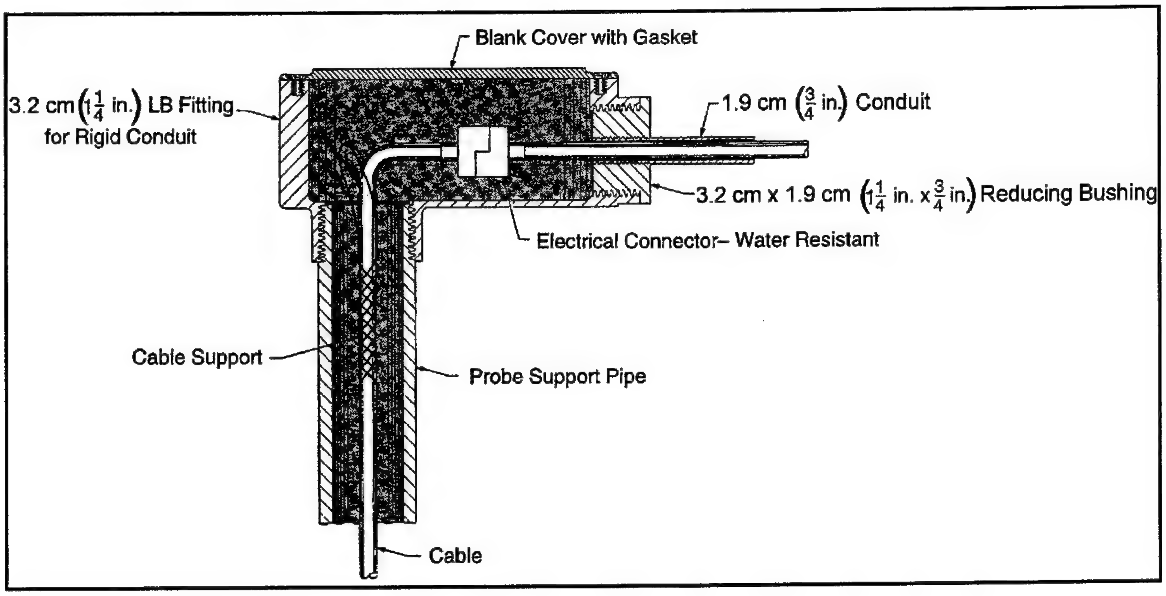


Figure 16-4. Connector box

Figure 16-5 shows a schematic diagram of the wiring of the interface box and the connections to the temperature probe and the DCP. The resistance of a thermistor R_i can be determined by the relation

$$R_i = (10{,}000)\frac{V_i}{V_o - V_i}$$

where V_i is the measured voltage across the thermistor, and V_o is the excitation voltage applied to the divider circuit. The applied voltage across the thermistor is kept low by the use of a diode. This is done to keep the electrical current in the thermistor to a minimum to prevent self-heating. The relatively large offset currents that may be introduced into the voltage divider circuits by the circuitry of the DCP itself result in an inaccurate voltage measurement across the thermistor. To correct for this, the voltage across a reference resistor, with a known stable resistance, is measured along with the voltage across the thermistor. The measured voltage across the reference resistor V_f can then be used to calculate each thermistor's resistance by

$$R_i = \frac{(10{,}000)\,V_i}{2V_f - V_i}$$

As an example, for V_i = 0.219 volts and V_f = 0.294 volts, the resistance of the thermistor of the water-temperature probe R_i is calculated by the above equation to be 5935 ohms. Suppose the calibration table for this particular thermistor is in degrees Celsius and gives 5951.3 ohms for 0.1°C and 5919.1 ohms for 0.2°C. Then, by interpolation the water temperature would be determined to be 0.15°C or 32.27°F. The foregoing discussion addresses some of the potential problems in interfacing input parameter signals to a DCP. In all cases the DCP manufacturer's input and output impedance specifications must be known and considered by competent electronics personnel for the proper design of the DCP interface box, thus ensuring a trouble-free overall installation.

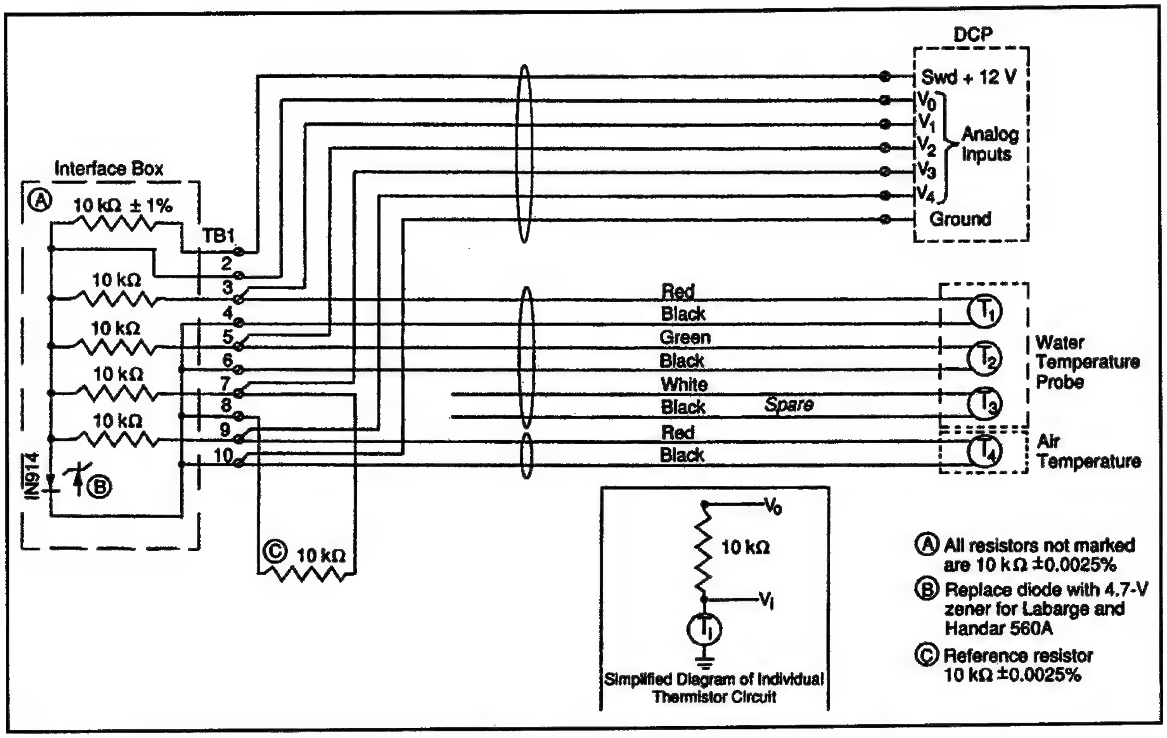


Figure 16-5. Schematic wiring diagram of DCP interface box

i. Installation. There are five steps in the installation of this water-temperature measurement system: selection of location, determination of minimum water surface elevation, installation of probe support pipe and adaptor, installation of the connector box and conduit, and installation of the data logger or DCP.

(1) Selection of location. The probe support pipe is typically installed on a wall or pier. The probe support pipe must be installed so that it is in contact with the moving river water. It should not be placed in gage wells, locks, or other areas where the water may stand for long periods. It should be placed in a protected location, if possible, so that it is safe from drift and ice floes. The downstream side of piers, cells, piles, pile dolphins, ladder accessways, and recesses in walls parallel to the river are acceptable.

(2) Determination of minimum water level elevation. River water level elevations or stages can change rapidly and can vary considerably. The difference between low flow levels and flood levels may be 12 to 24 meters (40 to 60 feet) in some locations. The minimum and maximum stage possible at a given site must be taken into account before installation. An estimate of the minimum must be made to ensure that the stage does not fall below the elevation of the water-temperature probe. If this happens, water temperature measurement will obviously not be possible. The bottom of the adaptor must be a minimum of 0.9 meters (3 feet) below the lowest stage expected. If very thick ice is expected, the adaptor should be placed even lower to keep the water-temperature probe in flowing water. The connector box should be above the normal seasonal high water levels.

(3) Installation of probe support pipe and adaptor. The probe support pipe must be installed vertically to allow the water-temperature probe to be lowered and removed easily. The length of pipe should be determined as follows: Measure the distance from the top of the wall to a point 0.9 meters (3 feet) below

the low water level elevation at the site. Subtract 0.15 meters (6 inches) from this distance. This will be the total length of schedule 80 pipe plus couplings that will be required. This will bring the top of the schedule 80 pipe 7.6 centimeters (3 inches) above the top of the wall, which is the correct height for the connector box. The required number of sections of the galvanized steel pipe are fastened together with couplings to form the probe support pipe. The adaptor is fastened on the lower end of the probe support pipe with a coupling. All couplings are tightened using a 0.6-meter (24-inch) pipe wrench to ensure that the entire probe support pipe and adaptor are securely fastened. The probe support pipe with the adaptor is raised into position by a crane or other means. Heavy-duty stainless steel straps are fastened at regular intervals with 1.3-centimeter (½-inch) Hilti quick studs or equivalent along the probe support pipe to hold it in position, again, with the bottom of the adaptor 0.9 meters (3 feet) below the lowest water level expected. The straps should be spaced using a maximum 1.5-meter (5-foot) interval up to the maximum water level elevation. Above the maximum water level elevation, a maximum spacing of 3 meters (10 feet) is allowable. The plumb of the probe support pipe should be checked continuously to make sure that the pipe remains completely vertical during installation. Otherwise, problems could occur with future probe removal or reinstallation.

(4) Installation of connector box and conduit. The connector box is threaded onto the probe support pipe. The connector box should be mounted such that the water-temperature probe can be placed in the probe support pipe through the top of the connector box with the cover plate removed. The connector box should be 7.6 centimeters (3 inches) above the wall so that it can be seen during snow removal. A reducing bushing is installed in the end of the connector box to adapt it to 1.9-centimeter (3/4-inch) conduit. Conduit is installed from the connector box to the point of data collection, with provisions for pull boxes where required.

(5) Installation of the data logger or DCP. The data logger or DCP is connected (Figure 16-5) to the interface box. Analog inputs to DCPs with scaling resistors should be avoided or the scaling resistors should be removed. If a data logger is used, a 12-volt-dc power supply must be provided. For consistency, the connections with the interface box should be in the order indicated.

16-5. GOES Satellite—WRSC Authorization

The Water Resources Support Center, Data Collection and Management Division (WRSC-C), has the responsibility and is the focal point for the U.S. Army Corps of Engineers Civil Works for call sign and radio frequency management.

16-6. Direct Ground Readout Station

The GOES system can only be used to relay environmental data. In situ data from any sensor that can be interfaced to the data collection platform can be telemetered to District offices. All the data transmitters that use the GOES/DCS must be certified by the National Oceanic and Atmospheric Administration, National Environmental Satellite Service. See ER 1110-2-248 for further instructions.

16-7. Water Control Data System (WCDS)

The receiving sites at the Corps offices are usually a part of the WCDS. Guidance for the management of dedicated water control data systems (including equipment and software used for the acquisition, transmission, and processing of real-time data for the purpose of regulating water projects that are the Corps' responsibility) can be found in ER 1110-2-249.

Section II
Imagery

16-8. Introduction

A necessary part of an ice management program is having adequate information on ice conditions. Corps Districts generally have one or both of the following objectives when documenting ice conditions as part of their river ice management activities: to analyze past ice conditions as an aid in forecasting future conditions during a given winter, and to monitor current conditions during a winter in sufficient detail so as to plan waterway operations and anticipate navigation problems.

a. Ice conditions information sources. The first objective can be accomplished using historical ground observations, aerial photographs, and satellite images. However, the most common District need is for monitoring current ice conditions along all their navigable waterways. At most navigation projects, Corps personnel already make ice observations and report them to District offices nearly every day during the winter season. The data are then available to users via computer modem. However, these ground observations are pertinent only for that portion of a waterway within sight of the observers. Ice conditions beyond that are uncertain, and yet such data for the entire waterway are required. Satellite images from current civilian satellites, which do show entire waterways, have neither the spatial resolution nor can they routinely be in the hands of District personnel quickly enough to enable decision-making regarding waterway operations or ice emergencies (Gatto et al. 1987a; Gatto 1988a, 1988b). As satellite sensors and image processing systems improve, future images may be provided rapidly enough and may be of sufficient resolution to be useful.

b. Current ice conditions. Aerial photographs and videotapes can currently provide timely ice information to meet the second objective above, i.e., monitoring current conditions (Gatto et al. 1986, 1987b). The acquisition of ice data from these two sources is the subject of the remainder of this chapter. Taking photographs is the best approach when it is only ice conditions at selected locations that must be documented. When continuous bank-to-bank coverage of ice conditions over large reaches of a waterway is required, vertical (downward-looking) aerial videotapes are most useful. Oblique videotaping can be done through an aircraft window, but this is awkward and uncomfortable for the videographer for extended periods, and complete bank-to-bank coverage is often difficult to obtain over large river reaches. Table 16-2 provides information comparing hand-held aerial photography and aerial videotaping.

16-9. Aerial Photography by Hand-Held Camera

Many photographic formats, film types, and cameras are available for taking aerial photographs. However, one of the least expensive and most useful formats is hand-held 35-mm oblique photography, producing slides or prints taken during low-altitude aircraft flights. The use of 35-mm photos for documenting general ice conditions and evaluating potential problem areas, e.g., ice jam sites, heavy ice, etc., is very appropriate when cartographic precision and photogrammetric quality are not required (Gatto and Daly 1986). Such photographs are simple and inexpensive to acquire and most people are familiar with them, as compared to other more elaborate aerial photographs.

a. Crew. The number of people required to get the photographs will vary depending on the complexity of the mission. When a few photographs of a small area are needed, one person can take them, even if that person is the pilot. A more complex mission would require three people including the pilot.

Table 16-2
Two Methods for Monitoring Ice Conditions on Navigable Waterways

Method	Equipment	Costs*	Advantages	Disadvantages
Hand-held aerial photographs	35 mm camera Color film for slides or prints Maps for locating photos in flight Fixed-wing aircraft** (e.g., Cessna 172)	$300 $3–$8/roll for slides, $7 for prints $1.50 each $60–$80/hr	Good resolution Different films can be used Low costs, once initial purchases are made Supplies and equipment readily available Camera systems are portable and flexible No extensive training required; most everyone is familiar with cameras Photographer can select targets	Can't take photos during inclement weather Takes a few hours to get slides or prints Ice thickness not obtainable; best guess only Snow-cover obscures ice Quality of photos unknown until they are developed
Aerial videotapes	Camera for ½ in. VHS or Beta, 3/4 in. U-matic On-board monitor Video recorders Camcorder (VHS) High grade color videotapes (T-120) Maps for locating tapes in flight Fixed-wing aircraft** (e.g., Cessna 172)	$1200–$5000 $ 600 $2500 (½ in.), $5000 (3/4 in.) $1600–$2200 $7/tape $1.50 each $60–$80/hr	Continuous view of river Immediate availability of tapes Operator sees image during acquisition; could correct problems in flight Low cost No extensive training required; familiar to many people Playback technology widely available Can get slides and prints from tapes Supplies and equipment readily available Tapes can be reused Videographer can select targets, if taking obliquely	Lower resolution than photographs but sufficient to differentiate ice types Can't take tapes during inclement weather Ice thickness not obtainable; best guess only Snow-cover obscures ice

* Costs will vary; these are simply estimates (1988 dollars).
** Helicopters can be used but cost more per hour.

One person would act as navigator to check items on the mission plan, direct the pilot to sites, take notes of sites photographed, change film, etc. The photographer would devote full time to taking pictures.

b. Mission plan.

(1) The photographer and navigator should prepare a general mission plan and discuss the plan and flight objectives with the pilot before a flight (Shafer and Degler 1986). They should discuss the features to be photographed and devise a way to communicate to let the pilot know when pictures are being taken. The pilot can then make a special effort to minimize motion and provide a good view of the area to be photographed. A professional pilot, with or without remote sensing experience, can contribute significantly by understanding what the flight objectives are.

(2) Mission planning will also permit more accurate estimates of materials needed, flight time, and overall costs for the mission. A mission plan should include a list of prospective targets and film requirements, maps marked with the most economical flight path, and a checklist of equipment, including extra batteries, lens caps, battery chargers, extra film, filters, etc. The maps help to avoid unnecessary

circling and the resulting questions regarding whether a particular site has been photographed or not. When maps are used in flight, a lapboard serves as a convenient writing surface.

c. Equipment (Shafer and Degler 1986). A 35-mm camera with a built-in automatic light meter and a standard (50-mm) lens is the minimum equipment needed. Optional but useful equipment includes a zoom lens, motor drive, data and magazine backs, and filters. The configuration of a camera system depends upon budget and photographic requirements.

(1) Either a single lens reflex (SLR) or rangefinder camera can be used effectively. With a rangefinder camera, the photographer must be aware that a clear shot through the rangefinder does not assure that the camera's field of view will not be partially blocked by part of the aircraft. With an SLR, what is seen is literally what is photographed. In difficult lighting situations where there is glare from aircraft windows, the SLR makes the photographer aware of potential problems so a correction for glare can be made during the flight.

(2) Regardless of what length of lens is used, it should be a relatively "fast" one (i.e, capable of admitting adequate light at higher shutter speeds) to avoid any loss of definition resulting from aircraft vibration. A zoom lens is useful because it allows the photographer to rapidly change for wide-angle and narrow-angle (more detailed) pictures.

(3) A motor drive permits obtaining several good exposures of a site during one pass. By simplifying the operation of the equipment, it also encourages the photographer to focus attention on the sites being evaluated, rather than concentrating on camera operation.

(4) Because of the high cost of aircraft rentals and the relatively low costs of film and processing, it makes sense to take a large number of pictures. However, labeling and sorting them is a chore at best. Data backs are particularly useful in recording the time and date, saving considerable time and effort later. Magazine backs (for up to 250 pictures) eliminate the need to change film frequently. They provide continuity during a flight and reduce the chance of error in numbering sequential rolls of film. They also permit the photographer to take many pictures with a minimum of costly time spent changing film. However, processing of long rolls (in excess of 36 exposures) must be done by a specialty lab. If a magazine back is not used, a second camera is a good investment. The navigator can reload one camera while the photographer is using the other.

(5) Regular true color film for slides (e.g., Ektachrome) and prints (e.g., Kodacolor) works fine for most conditions. A relatively fast film (ASA 100 or higher) with a fine grain is best.

(6) As a matter of course, clear filters should be on all lenses to protect them from dirt and damage. A polarizing filter may be used successfully with most films; however, the combination of a polarizing filter and the aircraft window may produce a wavy pattern on a picture. Usually, a polarizing filter improves the quality of photographs taken where reflections from water produce glare.

d. Taking photographs (Evans and Mata 1984). Aerial 35-mm pictures may be taken nearly vertically or obliquely out the window of a small, fixed-wing aircraft or helicopter. Shutter speeds should be 1/500th of a second or faster. An altitude of 450 meters (1500 feet) above the ground is recommended, but any altitude must be consistent with local Federal Aviation Administration regulations. If possible, shoot with the window open. This eliminates glare and reflection caused by the glass. If you have to shoot through the window, use an 81A filter, or an equivalent haze filter, to compensate for the slight blue-green

tint inherent in the acrylic glass used in most light airplane windows. Also, wear a long-sleeved dark shirt or jacket to reduce the chance of creating unwanted window reflections. Always use a lens shade. Window glare can often be eliminated by moving the lens slightly closer to the window or by draping the photographer and camera with a jacket or blanket to stop light passing over the photographer's shoulder. With a high-wing aircraft, the best shooting angles are in front of and behind the wing-struts. The front angle is best for tracking a subject, if care is taken to avoid getting the propeller in the frame. With a mid- or low-wing plane, pictures may have to be taken in a steep turn to avoid photographing the wing.

(1) A hand-held camera can take stereo pairs by photographing two successive images framed to get the same location. The movement of the aircraft between exposures will produce the parallax necessary for stereo viewing. The stereo effect will show the surface roughness of the ice, and this three-dimensional view is more realistic and easier to relate to actual visual observation. Panoramic mosaics of reaches of a river can also be made by taking as many successive photographs as required to cover the area of interest. Be sure to overlap successive photos enough to get complete coverage of the area. Note that the overlap areas will be in stereo.

(2) If repetitive photographs are going to be taken during different flights over periods of days, weeks, or months, the comparison of photos from the several flights will be easier if the same camera, focal length lens, filters, etc., are used each time. Taking photos from the same general position, and showing the same ground area, will also expedite comparisons of repetitive photos. Such repetitive photos give a visual time series of ice conditions, and are useful for determining how conditions are changing.

e. Photointerpretation. An advantage of using hand-held aerial photographs is that almost everyone has taken them and looked at, i.e., "interpreted," them. No special equipment is required to study the photos. The most important element for interpreting photos of ice conditions is to have a person familiar with river ice involved in the interpretation.

16-10. Aerial Videotapes

Aerial videotapes are more convenient to take than overlapping hand-held photographs if continuous coverage of a waterway is required and are less expensive than vertical 23 × 23-centimeter (9 × 9-inch) aerial photographs. Such continuous coverage can be acquired with a video camera mounted to look through the nose or out the side door of a helicopter, or through a belly port of a fixed-wing aircraft.

a. Crew. Since videotaping will generally be used to get continuous coverage, a pilot and videographer are all that is required. A navigator is not required because all of a waterway is going to be covered and site selection and spotting are not done. The pilot should be familiar with techniques for maintaining a flight course so as to get complete coverage while keeping the video camera in a vertical or near-vertical position. The videographer will have to use a zoom lens and tell the pilot when altitude adjustments are required to maintain bank-to-bank coverage.

b. Mission plan (Maggio and Baker 1988). Just as when acquiring hand-held aerial photographs, careful mission planning must be done to get useful videotapes. It is important to keep in mind that bank-to-bank coverage should be maintained while videotapes are being taken. This will allow easy locating later by comparing features on the tapes with those on maps. Widths of the waterway to be taped should be used to determine the flying heights and focal lengths required to provide bank-to-bank coverage and to determine the maximum aircraft speed to avoid image blur caused by forward image motion and aircraft vibration (see Table 16-3).

Table 16-3
Aerial Video Coverage Versus Pixel (Picture Element) Size, Altitude, and Aircraft Speed (Based on 2/3-inch Video Format)

SI Units

Coverage (m)		Effective Pixel Size* (m)	Altitude (Feet Above Ground) Required for Various Lens Focal Lengths					Maxmum Aircraft Speed** (km/h)
Width	Length		6.0 mm	8.5 mm	12.5 mm	16.0 mm	25.0 mm	
152	114	0.6	104	147	216	277	433	101
305	229	1.2	208	294	433	554	866	203
457	343	1.8	312	442	650	831	1,299	304
610	457	2.4	416	589	866	1,108	1,732	406
762	572	3.0	520	736	1,082	1,385	2,165	507
914	686	3.7	623	883	1,299	1,663	2,598	610
1,067	800	4.3	727	1,031	1,515	1,940	3,031	711
1,219	914	4.9	831	1,178	1,732	2,217	3,464	813
1,524	1,143	6.1	1,039	1,472	2,165	2,771	4,330	1,015
1,829	1,372	7.0	1,247	1,766	2,598	3,325	5,195	1,218
2,134	1,600	8.2	1,455	2,061	3,031	3,879	6,061	1,421
2,438	1,829	9.4	1,663	2,355	3,464	4,433	6,927	1,624
3,048	2,286	12	2,078	2,944	4,330	5,542	8,659	2,031
3,658	2,743	14	2,494	3,533	5,195	6,650	10,391	2,437

English Units

Coverage (ft)		Effective Pixel Size* (ft)	Altitude (Feet Above Ground) Required for Various Lens Focal Lengths					Maxmum Aircraft Speed** (knots)
Width	Length		6.0 mm	8.5 mm	12.5 mm	16.0 mm	25.0 mm	
500	375	2	341	483	710	909	1,420	55
1,000	750	4	682	966	1,420	1,818	2,841	109
1,500	1,125	6	1,023	1,449	2,131	2,727	4,261	164
2,000	1,500	8	1,364	1,932	2,841	3,636	5,682	219
2,500	1,875	10	1,705	2,415	3,551	4,545	7,102	274
3,000	2,250	12	2,045	2,898	4,261	5,455	8,523	329
3,500	2,625	14	2,386	3,381	4,972	6,364	9,943	384
4,000	3,000	16	2,727	3,864	5,682	7,273	11,364	439
5,000	3,700	20	3,409	4,830	7,102	9,091	14,205	548
6,000	4,500	23	4,091	5,795	8,523	10,909	17,045	658
7,000	5,250	27	4,773	6,761	9,943	12,727	19,886	767
8,000	6,000	31	5,455	7,727	11,364	14,545	22,727	877
10,000	7,500	39	6,818	9,659	14,205	18,182	28,409	1,097
12,000	9,000	47	8,182	11,591	17,045	21,818	34,091	1,316

* Effective pixel size based on 258 pixels per format width.
** To avoid forward image motion blur if not using shuttered camera or forward image compensation.

c. Equipment (Meisner and Lindstrom 1985, Meisner 1986). The type and setup of videotaping equipment (Figure 16-6) used to get vertical videotapes from an aircraft will depend on cost and requirements. Numerous cameras and recorders exist, and technology is improving constantly, but whatever kind of system is used, it should be professional-grade, compact, and built to take abuse, and should provide high quality video. Camcorders combine video cameras and recorders in one unit and also provide high quality tapes.

(1) The audio track of the airborne Video Cassette Recorder (VCR) may be connected to a "press to talk" microphone, allowing oral comments to augment written notes during flight. In particular, landmarks and locations should be called out. A soundproof headphone intercom system used in the aircraft can be directly connected to the VCR audio input.

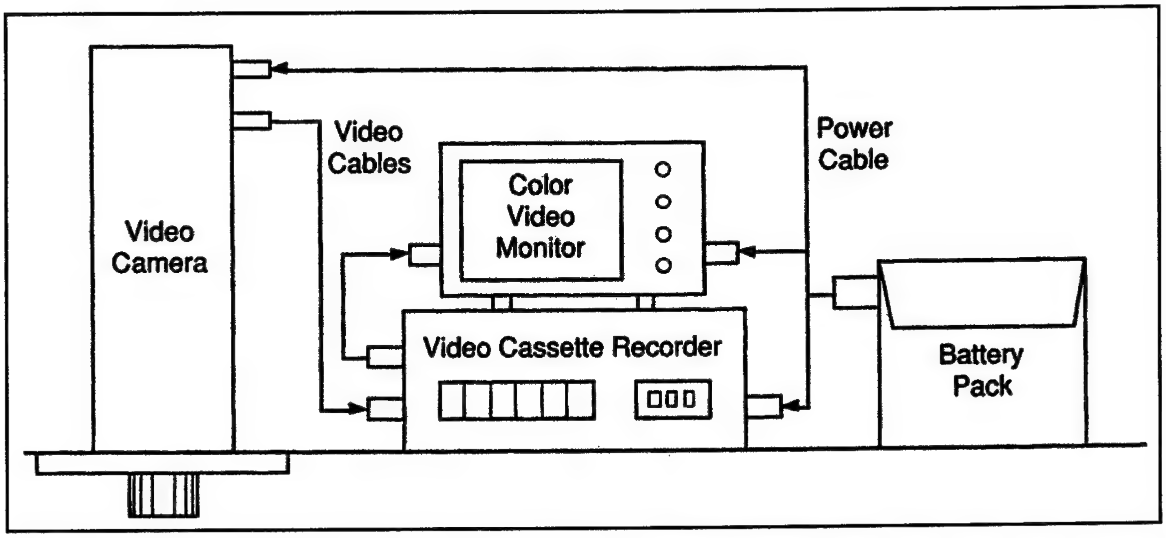


Figure 16-6. Generalized video equipment setup in an aircraft for vertical aerial videotaping (after Meisner 1986)

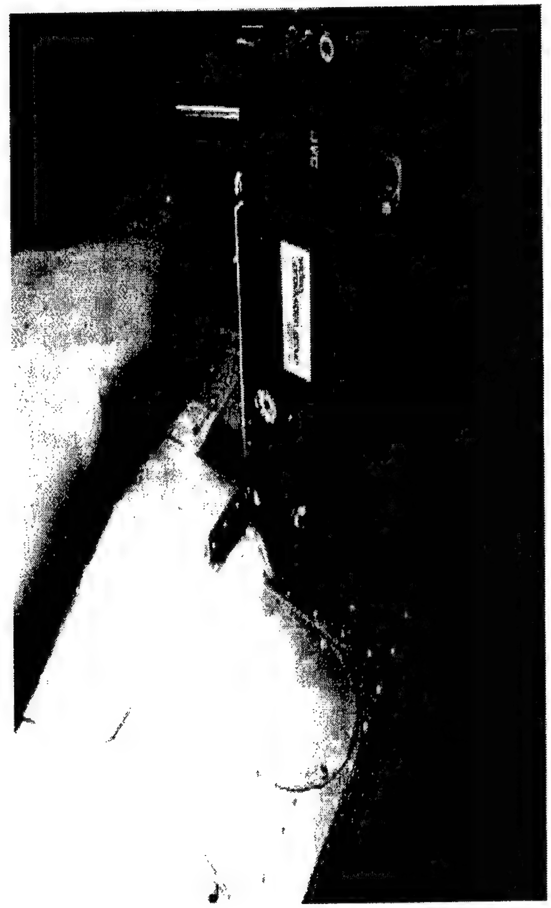
(2) Video monitors display the video image. Portable monitors generally have a 12.7-centimeter (5-inch) diagonal screen, providing a 7.6 × 10.2-centimeter (3 × 4-inch) image, although color monitors as small as 6.6 centimeters (2.6 inches)(screen size of 4.1 × 5.3 centimeters [1.6 × 2.1 inches]) are available and may be useful for airplane cockpit mounting. The video monitor must be located within the pilot's view to provide feedback for positioning and control of the aircraft. A sun shield on the monitor screen is essential for in-aircraft use. Interpretation in the office can be done with the portable monitor, but a larger screen is preferable.

(3) Power supply should be taken from the aircraft if possible. Airplanes operating on 12 volts should be able to power the system directly through the cigarette lighter outlet. Larger planes operate on 24-volt systems, requiring a dc adaptor to directly power the video system. Alternatively, power can be obtained from built-in, rechargeable battery packs or a rechargeable, sealed, lead–acid battery (gel cell).

(4) The playback video system used for interpretation in the office following the flight should have fast-motion, slow-motion, and still-frame capabilities. Of these, the still-frame (or freeze-frame) is the most important, since a single frame must be displayed if actual mapping is done during interpretation. The still-frame must be free from noise bars and hold steady on the screen. A playback VCR with stereo audio tracks is useful. This allows one track to be used for in-flight annotation, the other track for later interpretation comments.

d. Taking videotapes (Maggio and Baker 1988, Meisner 1986). The blur problem caused by aircraft vibration can be solved by properly mounting a video camera on the floor of an aircraft for taping through a port (Figure 16-7). Districts should be sure that contractors taking vertical videotapes have a mount that has been tested and proven to work. Forward-looking mounts would be useful for providing improved navigational assistance to the pilot. Forward-looking video also improves the ability to locate the imagery during interpretation. The background of each frame will show a wide area, giving more landmarks, while the foreground will provide larger scale for interpretation. Since whatever appears at one time in the background will later appear in the foreground, the continuous coverage nature of video imagery helps in this case. Even in applications requiring vertical coverage, a selectable forward

a. **Camera mount and viewing port**



b. **Camera in place for vertical videotaping**

Figure 16-7. Simple video camera mount in the floor of an aircraft for through-a-port videotaping

inclination would be very useful for navigating up to the start of a flight line. The camera could be tilted forward on the approach to the line, and returned to the vertical position at the start of the line.

e. Tape interpretation. In addition to the portable equipment used during tape acquisition in an aircraft, and a monitor for office use, some additional hardware can be useful when viewing the tapes in the office. The importance of a high quality still-frame capability has already been mentioned. High quality, four-head VCR's can provide a more steady image than compact portable units and may be worth obtaining for interpretation use. The best still-frame images are provided by a digital freeze-frame unit, also called a frame-grabber. Such a device converts a frame of imagery to digital data, stores it in computer memory, and regenerates a video image from the stored data. Unfortunately, these devices are quite expensive. Good quality prints, slides, and film negatives can be made directly from videotapes with a Polaroid Frame Grabber. As with 35-mm photographs, almost everyone has looked at videotapes, and the most important element in interpretation is to have a person who knows river ice, and has observed and studied it, be involved in the video image interpretation.

16-11. Ground-Based Video

a. Normal speed. Video systems consisting of battery-operated portable cameras and recorders, or combined camcorders, can be used to document ice conditions and other problems along a river. Rock Island District has supplied the lockmasters with these devices and is using them to document both wintertime and summertime problems. Such problems may be ones calling for special maintenance attention, ones suggesting operational or structural modifications, or ones that can potentially lead to litigation. These video systems are attractive because of the instant documentation that is available and the low cost of operation. When using a video camera for documentation, it is helpful to remember the following points. Known problem areas should be regularly documented, preferably from the same vantage point. A tripod should be used whenever possible to minimize motion in the picture. And finally, deliberate movement of the camera or lens (panning and zooming) should be minimized, and if done, done slowly.

b. Time-lapse. When a River Ice Management Plan is being developed and a problem area has been identified, it is desirable to obtain a complete record of observations of ice problems at that problem location throughout the winter. These problems are often concentrated at the upstream approaches of the locks, where broken ice becomes lodged, adversely affecting the operation of lock gates and the movement of tow traffic. Time-lapse videography permits the collection of an extensive record of these conditions without having personnel occupying the site continuously for the entire ice season. Time-lapse videography can be used to determine the causes of specific ice problems at a location or to monitor the effectiveness of ice control solutions. Time-lapse videography has been used successfully on the Ohio and Illinois rivers both to determine the causes of ice problems and to monitor the effectiveness of ice control measures at locks, such as high-flow air systems. At Emsworth Lock and Dam on the Ohio River near Pittsburgh, Pennsylvania, time-lapse videography has been used to observe the effects of winds, currents, and large tow traffic on ice movement into the upper lock approach since the winter of 1984–85. At Peoria Lock and Dam on the Illinois River near Peoria, Illinois, and at Starved Rock Lock and Dam on the Illinois River near Ottawa, Illinois, data have been recorded on the effects of winds, river currents, and large tow traffic on the movement of ice in the upper lock approaches. In addition, the effectiveness of high-flow air screens was monitored at the latter two sites. The time-lapse videographic records at Peoria have been taken annually since the winter of 1984–85, while records from Starved Rock are available since 1985–86. In addition to wintertime uses, various Corps facilities—e.g., Starved Rock Lock and Dam in Illinois and Lower Granite Lock and Dam on the Snake River in Washington—are using video cameras to monitor recreational boating, commercial navigation, debris control, and general facility security.

(1) Equipment. There are two general types of time-lapse setups that are available today, time-lapse photographic film cameras and time-lapse VCRs. Of the two, the VCR system is preferable (it is easier to work). While the initial cost of both systems is comparable, the VCR system is substantially cheaper to operate. The minimum equipment required for an ice monitoring time-lapse videographic system consists of the following:

- Time-lapse recorder with recording time ranges of 2 to 240 hours and monitor.
- Solid state imaging video-camera and zoom lens with a focal length range of 10–100 mm.
- Environmental camera housing capable of maintaining an interior temperature of 4.4°C (40°F) while the ambient air temperature can be as low as –51°C (–60°F). The camera housing should be mounted on a remotely controlled pan and tilt mount.

- Remote controllers for the pan–tilt mount and the zoom lens.

- Miscellaneous equipment such as mounting brackets, cables, relay boxes, etc., that may be required for a specific site.

(2) Installation. The camera is best installed in a high location, such as an antenna mast or the craneway over the dam gates. The VCR and various controllers should be located in a protected shelter where it is convenient to monitor the video and to change tapes. At a lock facility, this can be the lockmaster's office or one of the machinery buildings. The main requirements here are that the humidity be low enough that condensation does not form and the temperature be kept between 4.4 and 38°C (40 and 100°F). Figure 16-8 is a schematic of a typical installation. The problems encountered in placing cables for the controllers and the video signal may influence the choices for placing the equipment.

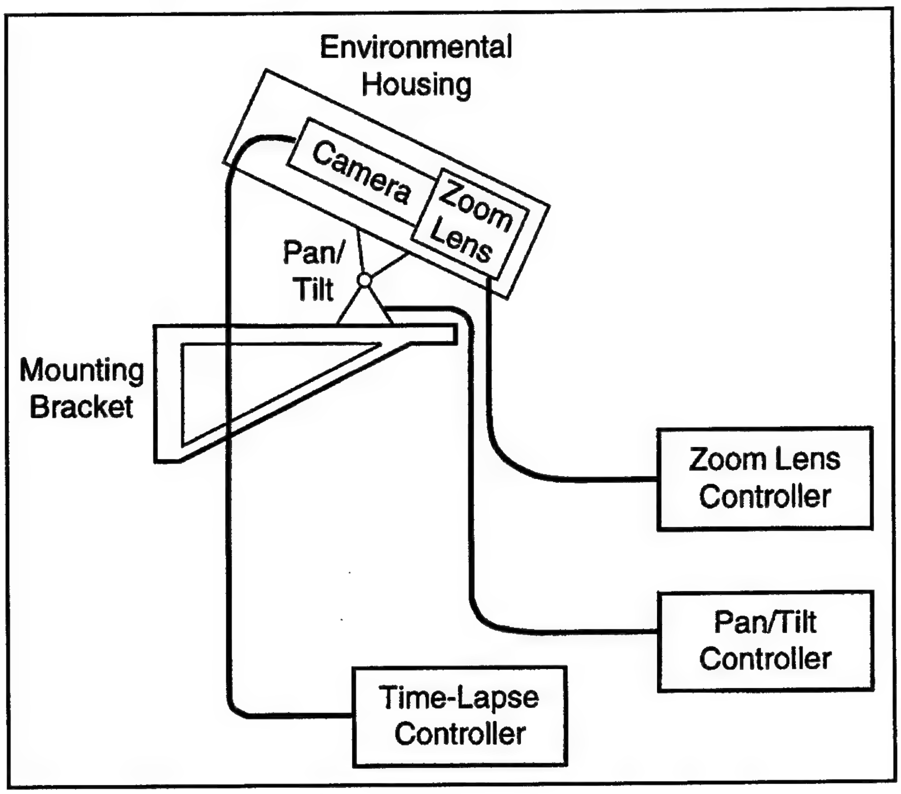


Figure 16-8. Schematic diagram of a ground-based time-lapse video system

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None.

b. Related publications.

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Chapter 17
Navigation in Ice

17-1. Introduction

A vessel navigating in ice must tolerate stresses imposed by an environment that is not encountered by regular shipping. The vessel's form, power, structure, and propulsion system must be designed to withstand these stresses. In addition, the effect of the vessel on the environment must be considered, as well as the effect of the environment on the vessel.

17-2. Environment

In winter a vessel may encounter sheet ice, brash ice, frazil ice, pressurized ice, a pressure ridge, ice with snow cover, or a combination of all these forms. The easiest of these to deal with is sheet ice—homogeneous ice with fairly uniform thickness. A properly designed vessel can travel through sheet ice, up to some limiting thickness that is a function of installed power.

a. Brash ice. The second type of ice, brash, is broken ice that fills a shipping channel with pieces up to 1.8 meters (6 feet) in diameter (Figure 17-1). Brash ice may fill the channel completely or partially and it can be unconsolidated or consolidated and refrozen. This type of ice, because of its lack of homogeneity, restricts vessel movement differently than does sheet ice.

Figure 17-1. Channel filled with brash ice

b. Frazil ice. The third type of ice is frazil ice. Frazil is highly cohesive in its active state. If the water velocity slows beyond a certain point, the frazil crystals can agglomerate and form a mush that can eventually block the channel to a large extent as well as solidify partially.

c. Pressure in the ice. All of these forms of ice can restrict traffic further if the ice sheet is under lateral pressure. Lateral pressure can be caused by wind or water currents. Ice sheets can also push over each other and form a pressure ridge. Such a ridge can grow to extreme depths and virtually block a channel.

d. Snow on the ice cover. The various types of ice described above can also be found with a snow cover. A snow cover does not affect the mechanical properties of the ice to any great extent; however, a snow layer increases the friction between the ice and the ship's hull.

17-3. Vessel Shape

Most vessels are designed to maximize the volume of cargo that they can carry; they tend to be rectangular with minimum curvature of the hull, the extreme example being the rectangular barge. Icebreakers are specifically designed for breaking and clearing ice, and have angled bows, special shapes, and are usually highly powered. Between these extremes are the blunt-bowed ore carriers, the raked-bowed barges, and passenger vessels.

a. Hull resistance factors. The resistance a vessel encounters in ice depends on its hull shape. The efficiency of a particular hull depends on the forces involved in breaking and clearing ice. Basically, a vessel breaks the ice by riding on top of it, causing the ice sheet to fail from tension in the lower and upper layers. After the ship breaks the ice sheet, it must clear the ice fragments from the channel. This is done by pushing the fragments down or to the side. The resistance of the ice to breaking and clearing is a function of the friction between the vessel and the ice and of the lateral pressure in the ice.

b. Variation in hull resistance. The resistance encountered by the vessel increases as the width and length of the vessel increase, as the thickness and strength of the ice increase, as the velocity of the vessel increases, as the friction between the ship and the ice increases, and as the lateral pressure in the ice increases.

c. Barge-hull resistance. In the case of a tug and towed or tug-pushed barges, the shape of the forward part of the hull has the largest effect on the resistance. A wide vessel with a plumb, blunt bow that has a very rough surface will encounter extreme resistance. If the bow is so blunt that the ice cannot pass to the side or below the vessel, the ice will pile up in front of the vessel, forming its own "bow" shape, and will eventually cause such high resistance that the vessel will be unable to move.

17-4. Auxiliary Icebreaking Devices

Several different methods have been developed to facilitate icebreaking and ice navigation. The most promising methods are:

- Low-friction hull coating

- Hull bubbler systems

- Air-cushion vehicles
- Auxiliary icebreaking devices.

These systems have been developed and refined by the U.S. Army Corps of Engineers, U.S. Coast Guard, Canadian Coast Guard, and ice researchers, as well as in Finland and Russia.

a. Surface friction. Figure 17-2 shows the coefficient of friction of various coatings, as well as that of steel on ice. The polyurethane and epoxy (nonsolvented coatings) proved to be the most effective in friction reduction and coating endurance.

b. Hull bubbler systems. Hull bubbler systems have been installed on several European icebreakers and on the latest USCG small lake icebreakers. Bubbler systems work by interposing air and water between the ice and the hull of the vessel. Figure 17-3a is a schematic of the bubbler system. Figure 17-3b depicts its deployment on a USCG icebreaker. Figure 17-4 shows the results of full-scale tests of the bubbler system on a European icebreaking ferry.

c. Air-cushion vehicles. The air-cushion vehicle (ACV) is the most dramatic contribution of modern technology to icebreaking. The vehicles can skim over the ice and break it at speeds of 5 to 32 km/hr (3 to 20 mph). The icebreaking occurs both at low speeds of advance as shown in Figure 17-5 (top) and at higher speeds of advance (bottom). At high speeds, the critical speed of the craft deflects the ice sheet to the icebreaking point. At low speeds, the air cushion extends under the ice, displacing the supporting water. Deprived of its support, the ice sheet fails under the pressure of the air cushion. Tables 17-1 and 17-2 show the results of tests conducted by the Canadian Coast Guard on ACV's. These tests indicate that an ACV can break ice whose thickness is 90 percent of the cushion pressure expressed in inches of water. The ACV has significant potential for aiding ice-jam flood control in shallow rivers and estuaries where vessel draft is limited. An ACV placed in front of a conventional icebreaker will increase its effectiveness.

d. Auxiliary icebreaking devices. A device that has been used in Russia and has been evaluated in the U.S. is the ice cutting vehicle. Such a vehicle cuts the ice with some apparatus such as a circular saw or a high-pressure water jet. The weakened ice is then either conveyed up onto the vehicle and thrown over the side, or deflected beneath and to the side of the vehicle by underwater ice guides. Figure 17-6 depicts conceptual sketches of two possible ice cutting and clearing devices. These devices could be used to keep channels in narrow rivers between locks and dams clear of ice. Another device is the icebreaking prow, which is attached to a conventional towboat in the same manner as a barge (Tatinclaux and Martinson 1988). Vanes fastened to the front and bottom of the prow break the ice and guide the ice pieces underneath and to the sides of the prow, where the ice accumulates under the adjacent ice cover. The opened channel behind the vessel/prow combination is left largely ice-free.

17-5. Summary

Vessels operating in ice must be given special consideration if they are to operate safely and efficiently. The vessel must have the power and structure to overcome the resistance and loads imposed by the ice environment.

a. Unassisted icebreaking. Properly shaped vessels with adequate power can break the sheet ice that is encountered on lakes and rivers. The primary problem is not so much sheet ice but brash and frazil ice that can fill the channel and cause unusually high resistance because of the friction between the ice and hull surface. This problem can be mitigated somewhat by a low-friction, high-wear coating.

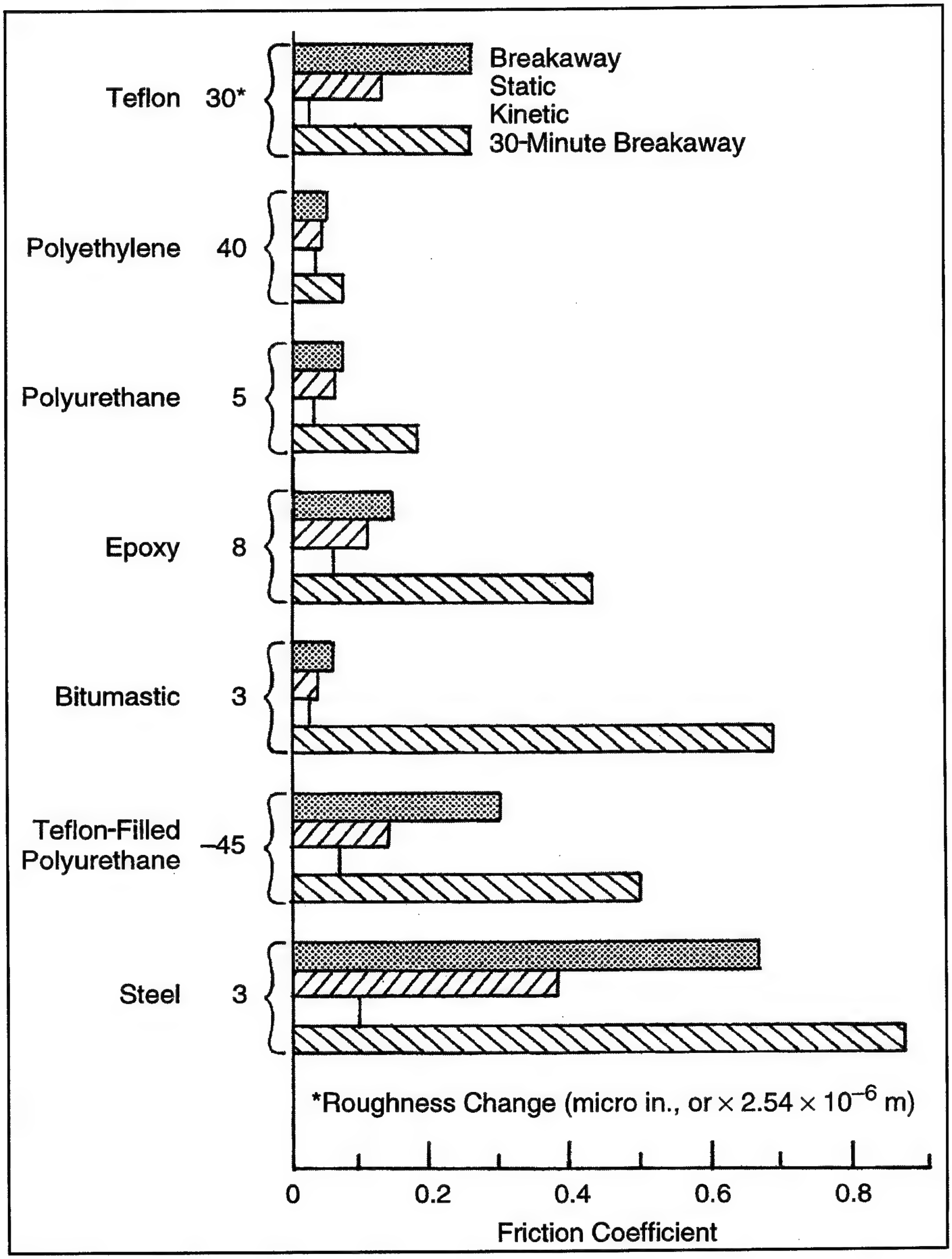
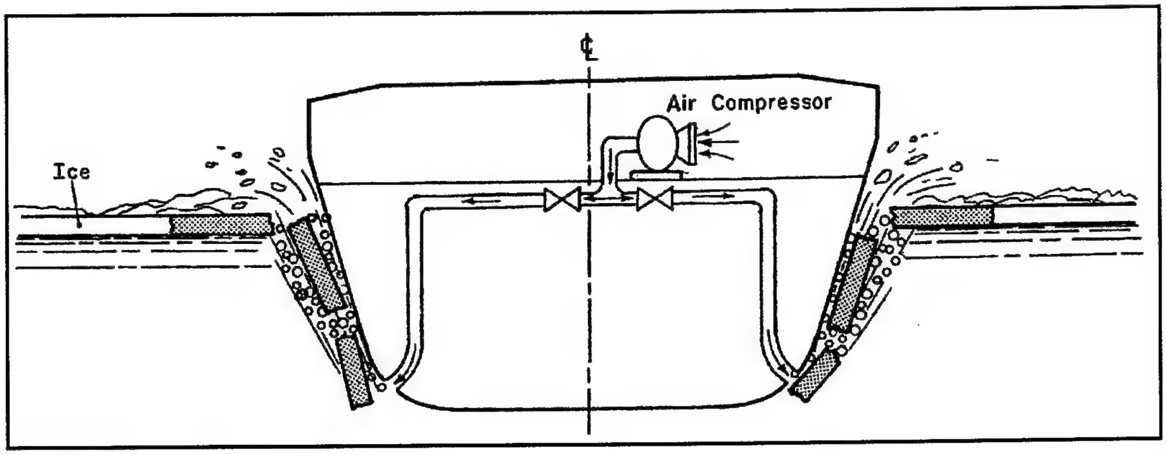
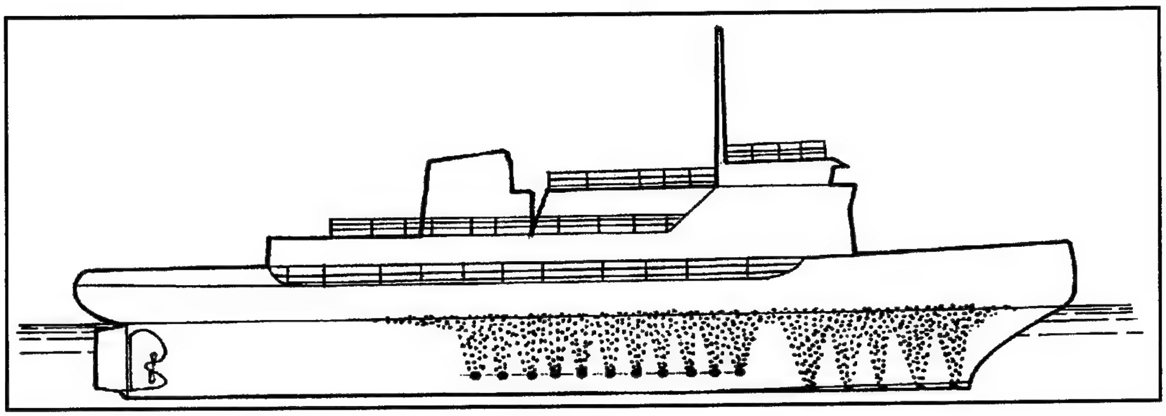


Figure 17-2. Coefficient of friction for steel and various hull surfaces on ice



a. Schematic



b. Bubbler installed on icebreaker

Figure 17-3. Hull air-bubbler system

Table 17-1
Air-cushion Vehicles Used in Trials and Operations

Vehicle	Gross Length m (ft)	Beam m (ft)	Vehicle Weight kg (lb)	Cushion Pressure kPa (in.) of H_2O
ACT-100	22.5 (73.8)	17.1 (56.1)	260,800 (575,000)	6.90 (27.7)
H-119	13.2 (43.3)	6.0 (19.7)	24,000 (53,000)	4.86 (19.5)
HJ-15	12.1 (39.8)	5.4 (17.7)	19,400 (42,700)	3.74 (15.0)
Voyageur	19.8 (65.0)	10.4 (34.0)	40,500 (89,300)	2.62 (10.5)
AC-80	6.0 (19.7)	3.5 (11.5)	1,300 (2,900)	1.0 (4.0)

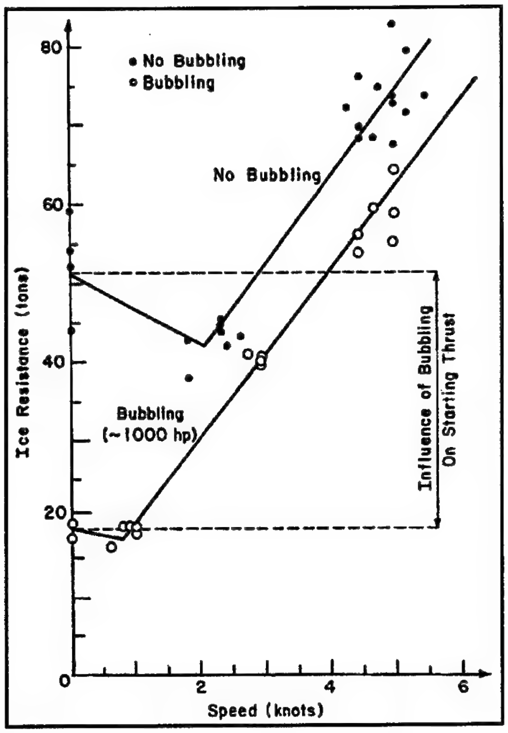


Figure 17-4. Air bubbler tests on a European icebreaking ferry

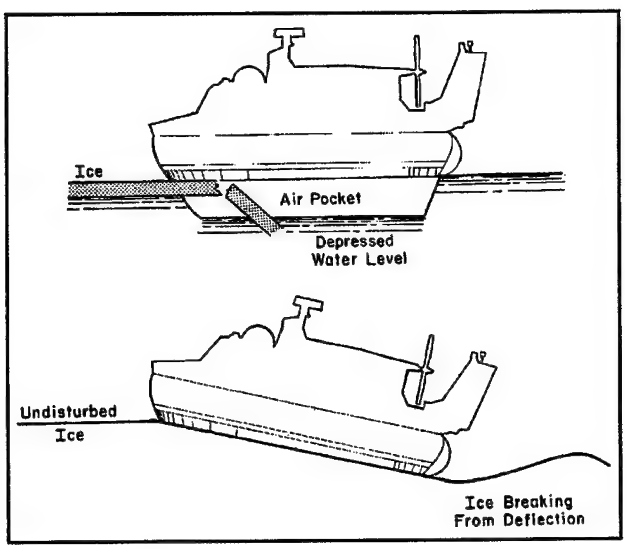


Figure 17-5. Air-cushion vehicle. *Top: Low speed icebreaking. Bottom: High speed icebreaking*

Table 17-2
Air-Cushion Vehicle Icebreaking Data

Vehicle	Date and Location	Ice Thickness, cm (in.)	Cushion Pessure kPa (in.) of H_2O	Speed km/h (mph)
ACT-100	1971 - YK	69 (27)	6.92 (27.8)	6-8 (4-5)
ACT-100	1972 - Tuk	51-56 (20-22)	6.23 (25.0)	6-11 (4-7)
H-119	1973 - Montreal	23 (9)	4.01 (16.1)	2-6 (1-4)
H-119	1974 - Toronto	23-25 (9-10)	2.64 (10.6)	6-10 (4-6)
HJ-15	1974 - Toronto	23-25 (9-10)	2.91 (11.7)	6-10 (4-6)
Voyageur	1974 - Parry Sound	23-25 (9-10)	2.49 (10.0)	8-11 (5-7)
Voyageur	1974 - Parry Sound	46-51 (18-20)	2.49 (10.0)	19-29 (12-18)
Voyageur	1975 - Montreal	up to 76 (up to 30)	2.0-2.5 (8-10)	19-50 (12-31)
Voyageur	1976 - Montreal	up to 102 (up to 40)	2.0-2.5 (8-10)	19-50 (12-31)
ACT-100	1976 - Thunder Bay	38-41 (15-16)	5.0 (20)	16 (10)
AC-80	1976 - Ottawa	20 (8)	1 (4)	8-10 (5-6)

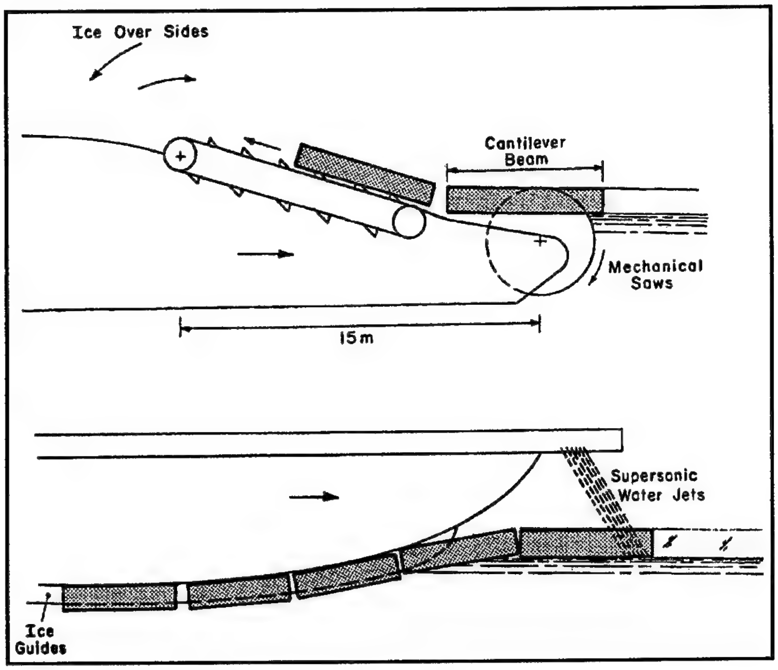
b. Cooperative programs. To enhance winter navigation on lakes and rivers, additional assistance is often required in the form of icebreaking, ice clearing, ice control, and towing or kedging. This assistance usually is provided by self-help programs of private industry. In certain limited cases, assistance is also provided by government agencies (principally the U.S. Army Corps of Engineers and U.S. Coast Guard).

17-6. References

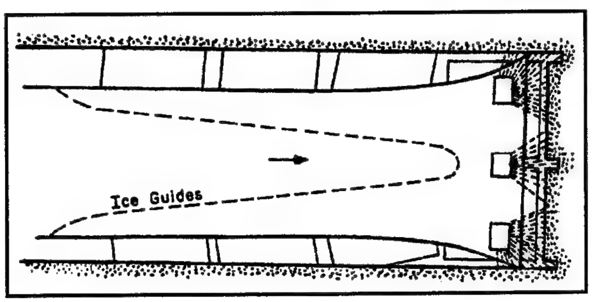
a. Required publications.
None.

b. Related publications.

Tatinclaux and Martinson 1988
Tatinclaux, J.-C., and C. Martinson. 1988. *Development of a River Ice Prow,* CRREL Report 88-9, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.



a. Type 1



b. Type 2

Figure 17-6. Ice cutter

Chapter 18
Structural Solutions for Navigation Projects

18-1. General

Ice problems at navigation locks and dams have been identified and grouped into ten categories. These are discussed in Chapter 14. Floating brash ice hinders normal lock operations and can delay barge movements for hours. Floating ice accumulations are often difficult to pass through dams to downstream reaches where the ice may pose fewer operational problems. Ice adhering to various lock surfaces interferes with the operation of lock machinery and can restrict the usable width of lock chambers. All of these problems can be addressed by various structural solutions which are discussed in this chapter.

Section I
Floating Ice Dispersion

18-2. Introduction

The most notable problems with brash ice are its entry into lock chambers, sometimes in heavy enough quantities to require separate ice lockages to pass the ice downstream, and its accumulation in miter gate recess areas, preventing the full opening of the gates. The most successful way to disperse ice is by means of high-flow air systems (Rand 1988). These systems may have up to three separate components, each with a specific function that increases the ease of lockage operations. (High-flow air systems are outgrowths of air bubbler systems intended to promote thermal thinning and weakening, i.e., melting, of ice; the latter are discussed in Part I, Chapter 3.)

18-3. High-Flow Air Systems

a. Distributed systems. Air manifolds should be placed in three specific locations around a lock to completely mitigate the problems of brash ice (Figure 18-1). First, a recess flusher should be placed in each gate recess; this will clear the recess area. The second manifold, called the screen, should be located just upstream of each set of miter gates. At the upstream edge of the gate forebays, there is typically a sill that runs across the lock chamber; place the screen on the downstream side of that sill. This screen keeps brash ice from entering the lock or, in the case of the downstream screen, clears ice from an area across the width of the chamber before the gate recess flushers are used. The third component is an optional one, depending on the physical layout of the lock and dam project. When there is some means for passing ice through or over a nearby spillway, the addition of a diagonal deflector in the upper lock approach can be an effective way to direct the floating ice toward the spillway. This manifold is typically installed using divers and weights because the area cannot normally be dewatered.

b. Single-point systems. Single orifices can be placed on the back wall of a floating mooring bitt recess. A single air line discharging at the bottom of the recess provides sufficient water turbulence to prevent floating ice from being pushed and packed between the float and the recess walls.

18-4. Air System Components

Each of the major components of high-flow air systems are discussed to clarify what is required and to provide information on physical size and placement of the components.

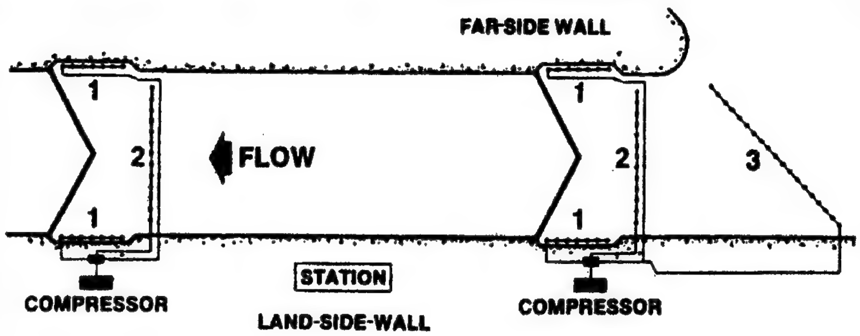


Figure 18-1. Schematic diagram of a complete high-flow air system, showing the three locations for air manifolds at a typical lock. *Two compressors are shown, but one large compressor with long supply lines could also be employed, assuming the supply lines are adequately sized*

a. Compressor. The air compressor of the size required is generally either diesel-powered or electrically operated. It can be either a permanent fixture or rented for the winter months. In a complete high-flow air system, the component requiring the most amount of air is the diagonal deflector. For a 33.5-meter-wide (110-foot-wide) chamber, a diagonal deflector manifold length of at least 61 meters (200 feet) is required. Design calculations (paragraph 18-6) will indicate that a compressor of at least 21.2-m^3/min (750-ft^3/min) capacity must be available. No more than one manifold should be used at any one time.

b. Supply lines.

(1) Pipes that run from a single, centrally located compressor to each end of the lock chamber must be large enough to handle the necessary air flow. One of the most common mistakes in designing an air system is undersizing the supply lines. Typically, at least a 7.6-centimeter-diameter (3-inch-diameter) schedule 40 pipe should be considered. If a supply length of over 152 meters (500 feet) is required, then a 10.2-centimeter (4-inch) pipe should be used for at least part of the total distance. Air control valves should be located at each end of the lock. Ideally, they should be remotely operated for easy use by the lock operator. The control valves allow the operator to selectively choose which air manifold to operate at any given time. An indicator should be provided to assure the operator that the valves are operating correctly.

(2) Supply lines from the control valves to the air manifolds submerged in the lock chamber vary in size, depending on the location of each manifold. The gate-recess flusher manifolds on the land wall require only a 5.1-centimeter (2-inch) pipe as a supply line (Figure 18-2). The gate-recess flusher manifold on the river wall, because of the added distance across the lock chamber to the manifold, needs to have at least a 7.6-centimeter-diameter (3-inch-diameter) supply line until the supply line reaches the far side of the lock chamber. The air screen going across the forebay sill requires at least a 7.6-centimeter (3-inch) supply line because of the volume of air being delivered (Figure 18-3). The location and placement of the supply lines may vary from lock to lock. It is best if the pipes can be located within the concrete walls,

Figure 18-2. A flusher on the land wall of the upper gate recess composed of a supply line and the manifold with orifices at Peoria Lock on the Illinois Waterway. *Note the vertical supply lines for the recess flusher of the river wall gate and for the cross-chamber air screen installed on the downstream-facing surface at the left (upper) end of the gate recess*

but if this is not possible, they should be located along the upstream edge of the gate-recess wall, protected from floating ice by steel plating.

c. Check valves. At the bottom of the vertical leg of each supply line entering the lock chamber, an in-line, spring-loaded check valve should be installed to prevent water from passing into the manifold through the orifices, entering the supply pipe, and freezing near the water surface when the air lines are shut off. This check valve must be removable by divers for replacement or repair if required.

d. Manifolds. The manifolds for each of the systems vary with the number of orifices and the size of the pipe. The design of an air manifold should provide for an even and uniform air flow through its entire length. To achieve this goal, the total area of the orifices must be less than 25 percent of the cross-sectional area of the manifold.

e. Recess flushers. The gate-recess flusher manifold differs from the other air manifolds because of the orifice spacing and pipe size. Laboratory and prototype analyses have shown that the spacing of the orifices should vary to provide more air near the quoin or pivot of the gate. The nominal spacings between orifices starting at the quoin end of the gate should be 1.2, 1.2, 1.2, 1.8, 2.4, 3, 3, and 3 meters (4, 4, 4, 6, 8, 10, 10, and 10 feet). The actual length of the manifold may vary because of lock constraints. Typically, in the locks on the Illinois Waterway, nine orifices are used.

f. Screens. The manifolds for the sill screens are designed with a 2.4-meter (8-foot) orifice spacing. For locks with a width of 33.5 meters (110 feet), a 29.3-meter-long (96-foot-long) manifold is used; 13 orifices are placed along that manifold.

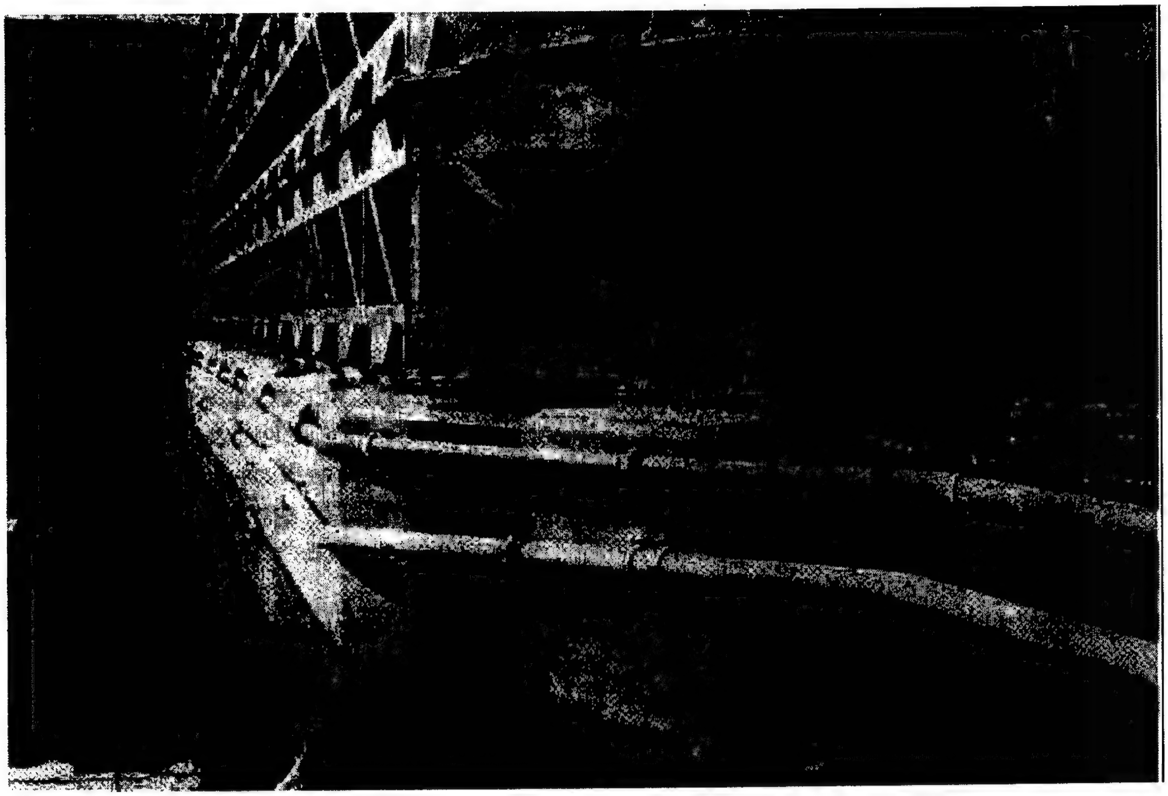


Figure 18-3. Downstream side of forebay sill, Peoria Lock. *Air-screen manifold (top pipe) and supply line for river wall gate-recess flusher (bottom pipe) are attached to the sill face with U-straps. There is an orifice at each pipe tee location in the manifold*

g. Deflector. For a diagonal deflector in the upper lock approach area, a 61-meter (200-foot) manifold is recommended, with 26 orifices.

h. Orifices. Each orifice is a drilled hole in a hex-head stainless steel pipe plug, which is installed in a pipe tee in the manifold line. The inside of the plug is slightly chamfered, and there is a sharp edge at the outside surface. The orifices are aligned so that the air discharges vertically. Occasionally, the orifices might become plugged with silt, so the manifold should be regularly operated throughout the year to help the orifices remain free of dirt. The orifice diameter ultimately controls the amount of air discharged. From laboratory analysis, it is recommended that a design flow of 0.85 m^3/min (30 ft^3/min) be provided for each orifice. This will provide sufficient air to create the desired effect at the water surface. For all the systems installed on the Illinois Waterway, 0.95-centimeter-diameter (3/8-inch-diameter) holes were drilled in the pipe plugs to serve as the orifices.

18-5. Effectiveness of the Air Systems

Experience gained from the use of complete high-flow air systems, as described above, has shown that the systems reduce winter lockage times, make for a safer operation, and keep the morale of lock personnel high. An average of 1 hour of compressor time is required to lock through an average tow. Some variation is experienced between individual operators, but all agree that a high-flow air system is an effective way to control floating ice problems at a lock (Figures 18-4 and 18-5).

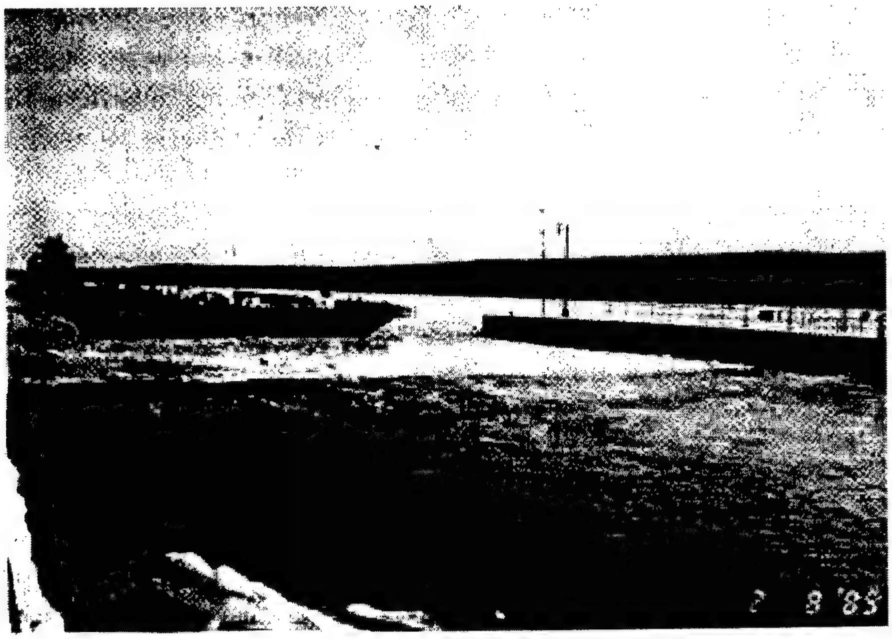


Figure 18-4. Upper screen in operation at Starved Rock Lock, Illinois Waterway. *Most brash ice is prevented from entering lock chamber, even with the entry of downbound tows*

18-6. Design of a High-Flow Air System

The parameters affecting the design of a high flow air system include: air volume and pressure available; effective length and size of the supply line; length and size of manifold line; depth of submergence; and orifice size and spacing. The air system analysis determines air discharge rates from an orifice by an iterative scheme that starts with a trial dead-end pressure. The analysis calculates the orifice discharge and pressure, starting from the end and working toward the supply point. After all the orifices are analyzed, the supply line pressure and air flow are calculated. The compressor pressure and flow rate necessary to sustain the supply line pressure and air flow are then calculated. The calculated compressor output is compared to the actual compressor output. The trial dead-end pressure is then adjusted and the analysis scheme repeated until the calculated and specified compressor outputs differ by no more than 1 percent. Changes in system parameters are made until the optimum design is obtained.

a. The calculations for optimizing the air system parameters are provided below. The initial trial dead-end pressure (P_d) is taken as

$$P_c = P_V + \frac{(P_U - P_V)}{4} \qquad (18\text{-}1)$$

where

P_c = true compressor pressure

$P_w = \rho_w g H$ = hydrostatic pressure

Figure 18-5. Gate-recess flusher in operation at Starved Rock Lock. *The ice is flushed away from the recess area, allowing the miter gate to be fully opened*

ρ_w = mass density of water

g = gravitational constant

H = submergence depth.

The subsequent trial dead-end pressure (P_d) is determined by

$$P_{d(new)} = P_V + \left(P_{d(old)} - P_V\right)\left(\frac{P_U - P_V}{P - P_V}\right) \tag{18-2}$$

where

P = calculated compressor pressure

$P_{d(old)}$ = old trial dead-end pressure

$P_{d(new)}$ = new trial dead-end pressure.

The air discharge rate (Q_o) from the orifices is calculated by the discharge equation

$$Q_o = C_d \frac{\pi d^2}{4} \sqrt{2 \Delta P / \rho_a} \tag{18-3}$$

where

C_d = discharge coefficient, sharp-edged circular orifice

d = orifice diameter

ΔP = pressure difference between inside and outside of diffuser line

ρ_a = mass density of air.

Finally, the pressure drop attributable to friction between orifices and in the supply line (ΔP_f) is calculated using the friction loss equation for turbulent flow conditions

$$\Delta P_f = \frac{f \rho_a \ell v^2}{D 2g} \tag{18-4}$$

where

f = friction factor

ℓ = equivalent length of pipe

v = air velocity

D = pipe diameter.

b. A computer program analyzing diffuser lines and nozzles gives a numerical simulation of air bubbler systems and is used for the air screen analysis. The input data include: diffuser line length and diameter, supply line length and diameter, orifice diameter and spacing, nominal compressor pressure, and submergence depth. The output from the program lists the following parameters: hydrostatic pressure, calculated output pressure, calculated compressor discharge, friction drop in diffuser line, friction drop in supply line, and excess dead-end pressure. To illustrate how changes in the system parameters affect the operating characteristics, Figures 18-6 and 18-7 show the effect on changes in the flow through an orifice with respect to changes in orifice diameters.

18-7. Example

A compressor with an output of 0.543 m^3/s (1150 ft^3/min) at 759 kPa (110 lb/in^2) was available for the high-flow air screen trials at the Soo Locks. Optimum air flow conditions could be obtained from a 5.1-centmeter-diameter (2-inch-diameter) manifold and supply line system with nozzles of 10-millimeter

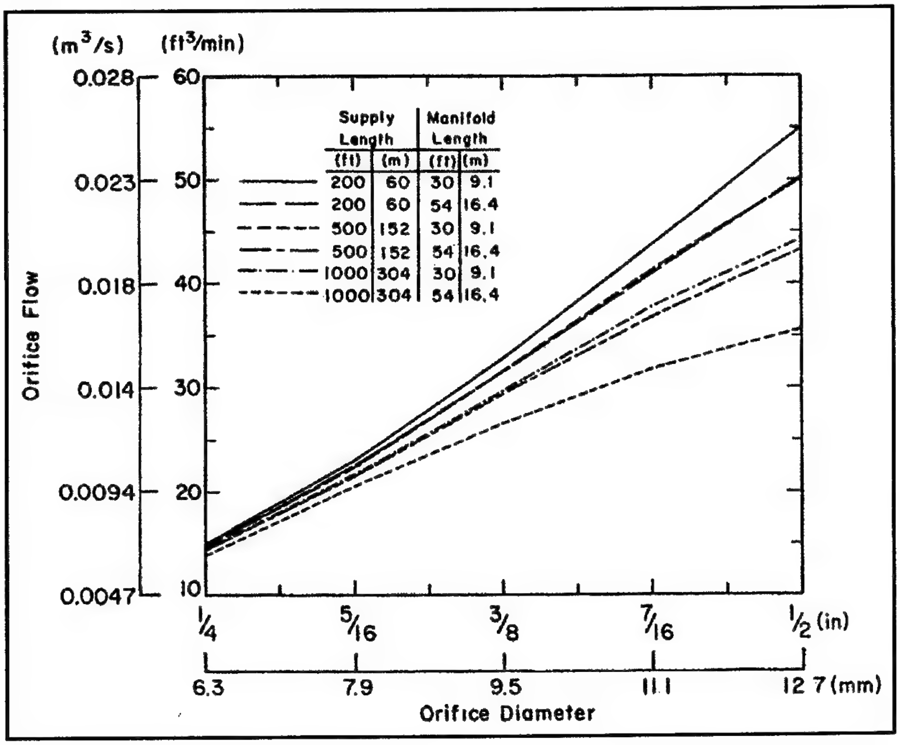


Figure 18-6. Performance curves for gate-recess flushers, showing the average air discharge from each orifice plotted with respect to orifice diameter, for combinations of three supply-line lengths and two manifold lengths. *The 5.1-centimeter (2-inch) diameter manifolds are either 9.1-meters (30-feet) nominal length for 17.1-meter (56-foot) wide locks, or 16.5-meters (54-feet) nominal length for 33.5-meter (110-foot) wide locks, submerged 6.1 meters (20 feet) below the water surface. Six orifices at nominal spacings of 1.2, 1.2, 1.2, 1.8, and 2.4 meters (4, 4, 4, 6, and 8 feet) are present in the 9.1-meter (30-foot) manifolds, and three additional orifices at nominal 3.0-meter (10-foot) spacings are present in the 16.4-meter (54-foot) manifolds*

(0.40-inch diameter), spaced 3 meters (10 feet) apart. The manifold line was 5.1-centimeter (2-inch) galvanized pipe with 5.1- × 5.1- × 2.5-centimeter (2- × 2- × 1-inch) tee joints each 3 meters (10 feet) of pipe. A 2.5-centimeter (1-inch) stainless steel plug was mounted at each tee and each plug had a 10.3-millimeter (0.406-inch) hole drilled in it that acted as the nozzle or orifice. The supply line riser, which ran up the side of the lock, was also of 5.1-centimeter (2-inch) galvanized pipe. A flexible, quick-disconnect hose joined the bottom of the riser to the horizontal manifold line. Flexible hose was also used from the top of the riser to the compressor.

a. The high-flow air screen was installed at the upper approach to the Poe Lock on the downstream, vertical face of an emergency stop-log gate sill. The sill is located about 61 meters (200 feet) above the lock gates. The riser line was installed in the stop-log recess in the wall. The width of the lock at this point is 33.5 meters (110 feet) and the height from the top of the sill to the top of the lock wall is 11.9 meters (39.2 feet).

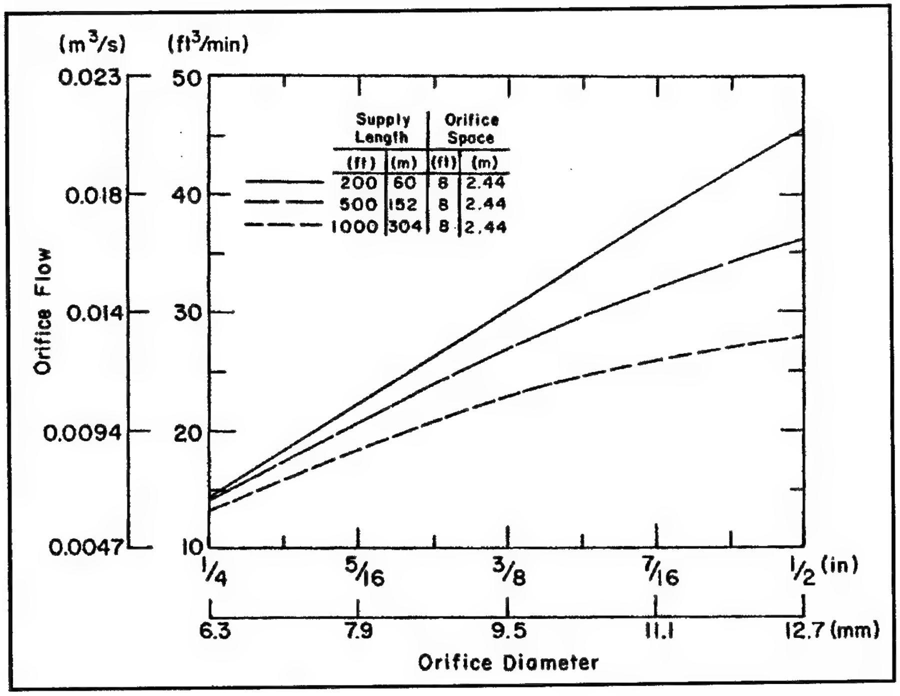


Figure 18-7. Performance curves for an air screen, showing the average air discharge from each orifice plotted with respect to orifice diameter, for three supply-line lengths. *The 6.4-centimeter (2.5-inch) diameter, 29.3-meter (96-foot) long manifold is typical for a 33.5-meter (110-foot) wide lock, and has 13 orifices at 2.4-meter (8-foot) spacings, 6.1 meters (20 feet) below the water surface*

b. The manifold line was installed at a depth of 10.5 meters (34.5 feet) in December 1977 and was assembled into four sections: two sections 8.46 meters (27.75 feet) long and two sections 7.47 meters (24.5 feet) long. Union connections joined the sections. The riser was assembled in one 11.7-meter (38.5-foot) section. The sections were light in weight; two to three people were able to move them by hand. All equipment for a hard-hat diver and the assembled pipes were placed on a 30.5-meter (100-foot) barge that acted as the working platform. The barge was positioned above the sill, and sections were lowered on ropes to the diver below who made the union connections and strapped the line to the concrete sill (Figures 18-8 and 18-9). One flexible hose coupling, from the diffuser to the riser, was also made underwater. The above-water installation process consisted of simply connecting a 15.2-meter (50-foot) flexible hose from the top of the riser line to the compressor. A 37,900-liter (10,000-gallon) fuel tank was placed beside the compressor to supply fuel (Figure 18-8) throughout the winter when delivery would be difficult.

c. The high-flow air screen was put into operation on 12 January 1978 when ice started to cause problems with lock operations. It was continuously available for service until 30 April 1978, except for a 5-day repair period in late March. By 1 May, ice no longer caused problems requiring the air screen, and the rented compressor was returned. During the 104 days of operation, the total running time on the compressor was 754 hours. Total consumption of No. 1 fuel oil was about 29,300 liters (7750 gallons).

d. The high-flow air screen demonstrated that it could hold back ice pushed ahead of downbound traffic. With ships in the 21.3-meter (70-foot) beam class, the ice was held back until the bow entered the air stream. The screen was not as effective with the wider 32-meter (105-foot) beam ships. Once the

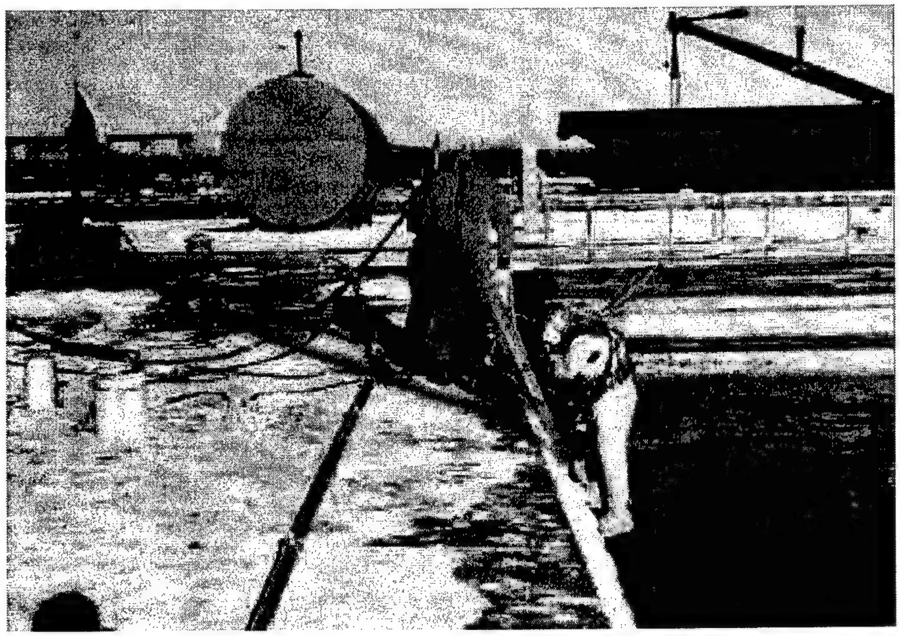


Figure 18-8. Diver working to install air screen system

bow of a wider vessel passed the nose pier (about 40 meters [130 feet] upstream of the screen), the approach was just a little over 33.5 meters (110 feet) wide, so most of the ice remaining in the track was pushed into the lock by these larger ships. This problem possibly could have been solved by relocating the air screen upstream of the nose pier area and by providing some area for the ice to be pushed outside the vessel track.

e. The merits of the air screen cited by lock operating personnel, besides the reduction in vessel lockage time, were savings in wear and tear on the lock gate and operating mechanisms, and savings in the time and effort required to remove ice collars from the lock walls. (The ice collars at the Soo result in part from the vessels packing brash ice against the lock walls.)

18-8. Flow Inducers

A common technique to move ice in and around the lock is the use of a towboat's propeller wash to induce a flow that moves the brash ice. The towing industry assists itself and the Corps lock personnel on occasion; towboats break away from their tows and flush sections of a navigation project. Another type of flow inducer used in the past, a submergible mixer, develops a flow in the top layer of the water to aid in moving debris or floating ice. An example of this operation formerly existed at the Chicago Harbor Lock, where submergible mixers were attached near the sector gates. However, they have been removed. To prevent ice from accumulating in front of lock miter gates that are not functioning during the winter months, several Districts have made use of commercially available flow inducers designed for the marina industry for protecting docks.

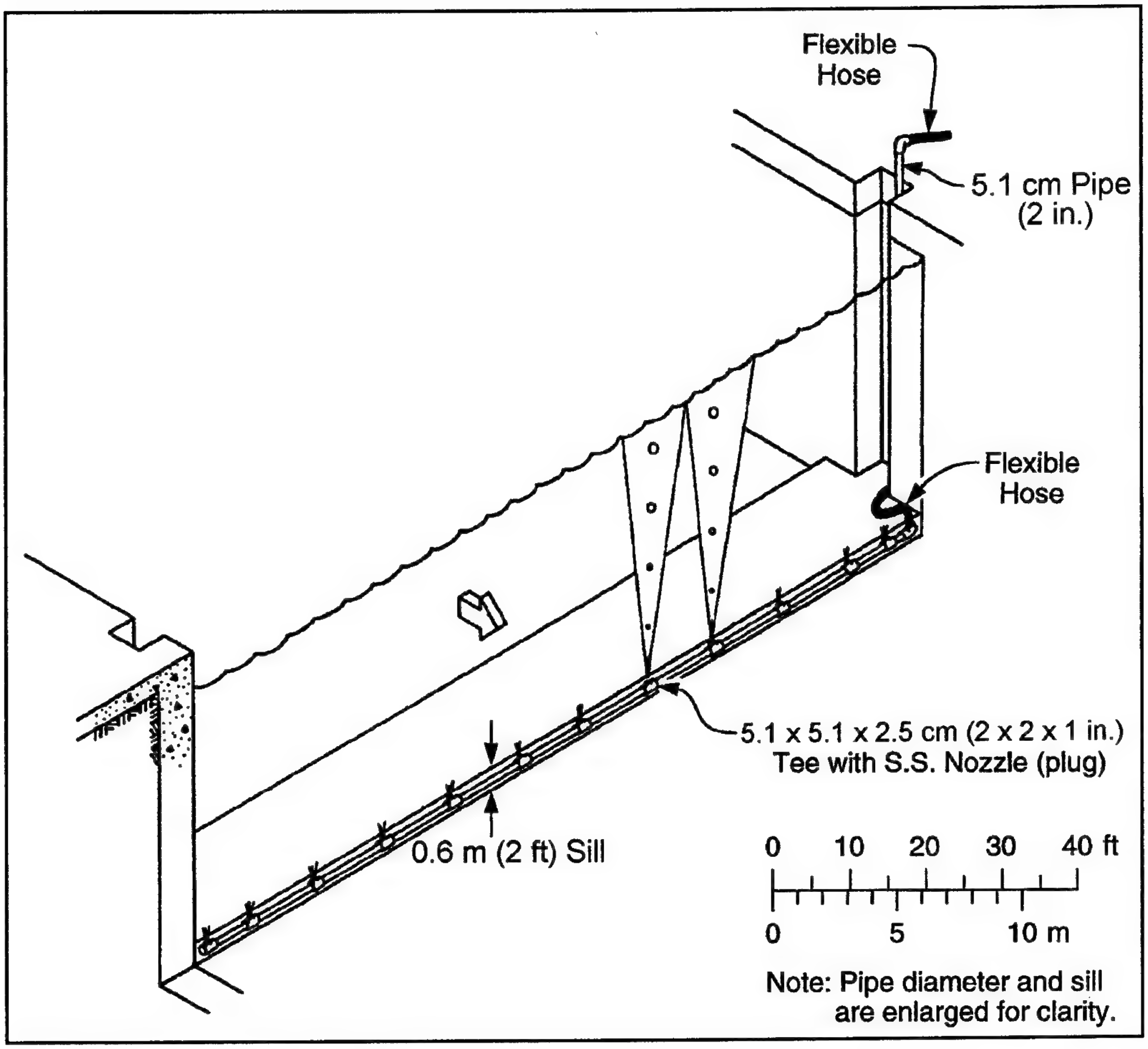


Figure 18-9. Schematic of an air screen

Section II
Ice Passage Through Dams

18-9. Introduction

The question of holding ice or passing ice from one navigation project to the next is a subject of great concern on all river systems. A definitive position on this problem cannot be taken. It is clearly understood that growing a stable ice cover will reduce the overall quantity of ice grown because of the reduction in frazil generation. However, the broken ice within the frozen ship track has to be dealt with every time a vessel passes through. Just upstream of the locks is a particularly unfavorable spot to allow ice to accumulate. Almost every lockmaster will state that he wants to keep that zone above his lock clear. The specific policy, however, will have to be addressed in each of the river systems.

18-10. Submergible Tainter Gates

A case study of use of submergible gates at Corps projects was prepared by the Louisville District (U.S. Army 1985). Each of the project sites discussed in the study has a variety of dam gates. In the past, the use of submergible gates to pass ice in the former North Central Division was encouraged, whereas the former Ohio River Division did not allow the existing submergible gates to be operated. (These former separate divisions are now represented by the Great Lakes and Ohio River Division and by a portion of the Mississippi Valley Division.) The specific problems and comments regarding the varied use of submergible gates are well documented in the Louisville report. Figure 18-10 summarizes many of the submergible gates considered in the study. A recent rehabilitation project on the Illinois Waterway installed submergible gates at Marseilles Dam specifically for improving ice passage. The major problem with passing ice is having sufficient water flow in the river system to open the gates, while maintaining adequate river stage. If broken ice is flowing toward the dam and the gates can be opened, a submergible gate will pass more ice than a nonsubmergible gate, given the same conditions. But it is more common that there is insufficient surface velocity to move ice toward the gate area. When this is true, the better ice passage characteristics of submergible gates provide no benefit. Moreover, ice bridging upstream of the gate, between the dam piers, is a common problem. However, a benefit of using submergible gates is that, since the gate is kept under the water, many gate freezeup problems are eliminated.

18-11. Roller Gates

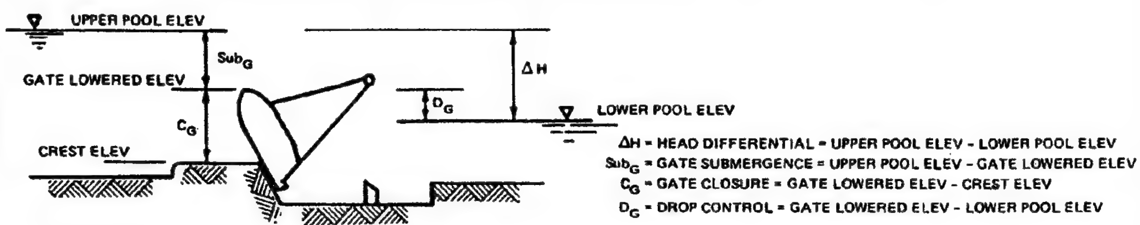
Roller gates are used extensively on the Mississippi River. At some projects they are lowered to a fixed submerged setting in the late fall and are kept in that position for the duration of the winter. The pools are then maintained by adjusting tainter gates. At other projects, the tainters are left to freeze in and the roller gates are adjusted, either submerged or with a bottom opening, to maintain upper pool stages. (At Lock 10 in the St. Paul District, the roller gates are not designed to be submergible, but they are the operative gates in winter.) In the cases where the roller gates are used in the submerged mode in winter, they may assist in ice passage, functioning in the same manner as submergible tainter gates, but having the same limitations. Other problems associated with roller gates are largely related to the lifting mechanisms, in which ice interferes with lifting chains, guide channels, and gear racks.

18-12. Conventional Tainter Gates

The openings required for ice passage at conventional tainter gates are usually quite large owing to the very high flow velocities needed to sweep floating ice downward to the bottom openings. As a result, except during periods of flood flow, these large openings normally cannot be used because of the likelihood of downstream scour at low tailwater stages. Thus, during the customary low-flow conditions of the winter season, ice passage at these gates is not feasible.

18-13. Gate Limitations in Winter

As detailed in Chapter 14, paragraphs 14-4*g* through *i*, successful operation of dam gates in winter, regardless of gate types, is impeded by accumulated forebay ice, by ice buildup on gate and pier structures from spray and splashing, and by the freezing of leakage past gate seals. All of these factors combine to render ice passage through gate bays very difficult and unreliable, unless remedial measures, as discussed in the following section, are employed.



Lock and Dam (COE District)	*River*	*ΔH*	*Sub_G*	*C_G*	*D_G*	*Problem*	*Remarks*
Greenup (Huntington)	Ohio	32.0	7.0	28.0	25.0	Yes	Problem: stilling basin and sill erosion and vibration Solution: submerged operation eliminated, plans and specs for modification as of Dec 1978
Meldahl (Huntington)	Ohio	30.0	7.0	28.0	23.0	Yes	Problem: stilling basin and sill erosion and vibration Solution: submerged operation eliminated
Markland (Louisville)	Ohio	34.0	7.0	33.0	27.0	Yes	Problem: vibration and jet through stilling basin and across end sill Solution: gate stops added and spillway curve modified. Submerged operation eliminated
McAlpine (Louisville)	Ohio	37.0	7.0	12.0	30.0	Yes	Problem: bed-material abrasion of sill Solution: submerged operation eliminated, spillway curve modified
Cheatham (Nashville)	Cumberland	26.0	7.0	19.0	19.0	Yes	Problem: vibration Solution: submerged operation eliminated, design and modification being considered
New Cumberland (Pittsburgh)	Ohio	22.6	7.0	12.5	15.6	Yes	Problem: vibration, cavitation between gate and sill, and recreational craft hazard Solution: submerged operation eliminated
Pike Island (Pittsburgh)	Ohio	21.0	7.0	20.0	14.0	Yes	Problem: excessive leakage Solution: submerged operation eliminated
L&D no. 4 (Pittsburgh)	Monongahela	16.6	7.0	12.5	9.6	No	Movable crest or piggyback gate
Maxwell (Pittsburgh)	Monongahela	19.5	7.0	19.0	12.5	No	Movable crest or piggyback gate
L&D no. 11 (Rock Island)	Mississippi	11.0	8.0	12.0	3.0	No	13 gates
L&D no. 12 (Rock Island)	Mississippi	9.0	8.0	12.0	1.0	No	7 gates
L&D no. 13 (Rock Island)	Mississippi	11.0	8.0	12.0	3.0	No	10 gates
L&D no. 16 (Rock Island)	Mississippi	9.0	8.0	12.0	1.0	No	3 of 15 gates
L&D no. 17 (Rock Island)	Mississippi	8.0	8.0	8.0	0.0	No	8 gates
L&D no. 18 (Rock Island)	Mississippi	9.8	5.0	15.0	4.8	No	14 gates
L&D no. 20 (Rock Island)	Mississippi	10.0	3.0	17.0	7.0	No	6 of 40 gates
L&D no. 21 (Rock Island)	Mississippi	10.5	8.0	12.0	2.5	No	10 gates
L&D no. 22 (Rock Island)	Mississippi	10.5	8.0	17.0	2.5	No	1 of 10 gates
L&D no. 24 (St. Louis)	Mississippi	15.0	8.0	17.0	7.0	Yes	15-80 ft TG's, vibration, stress on trunion; submerged operation eliminated
L&D no. 25 (St. Louis)	Mississippi	16.0	7.0	18.0	9.0	Yes	14-60 ft TG's, vibration stress on trunion; submerged operation eliminated
L&D no. 26 (St. Louis)	Mississippi	24.0	3.0	27.0	21.0	No	30-40 ft TG's

Figure 18-10. Summary of submergible gates and their problems. *Many of these were considered in the Louisville District study of the use of submergible gates for passing ice (U.S. Army 1985)*

18-14. Other Ice Passage Schemes

Ice can be successfully passed at some navigation locks having auxiliary lock chambers and bulkhead lift systems by skimming the ice over partially raised bulkheads. Figure 18-11 shows such an operation. This appears to be an effective way to pass ice through the lock system, thus clearing the upper approach area.

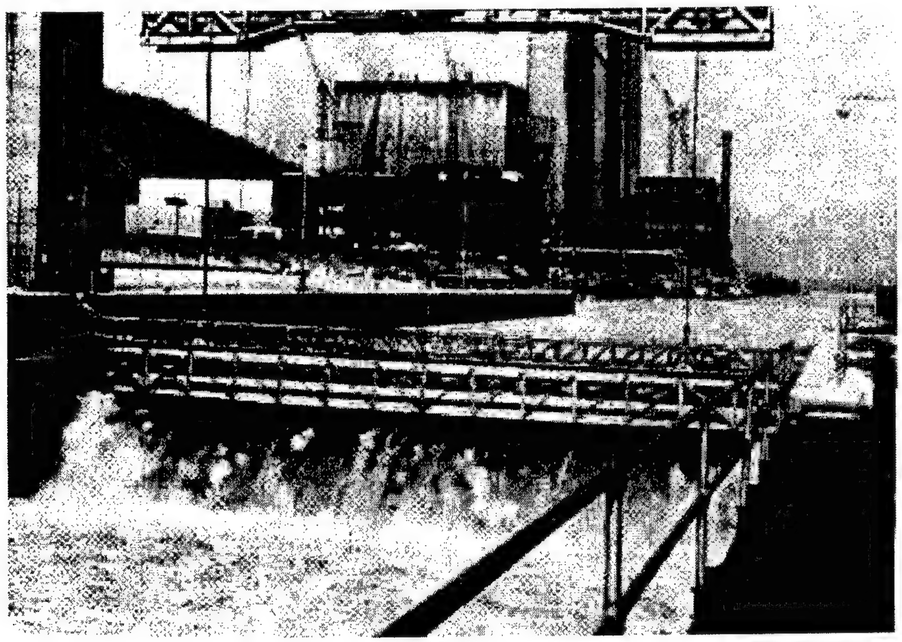


Figure 18-11. Ice passage at New Cumberland Lock on the Ohio River. *The partially raised bulkhead of the auxiliary lock chamber allows flow to carry ice out of the lock approach area*

Section III
Anti-Icing and Deicing at Locks and Dams

18-15. Introduction

As described in Chapter 14, the ice-related problems at navigation structures are severe during the winter months. Exposed mechanically operated systems may be frozen-in and become inoperable. The weight of ice formed on structures that need to be lifted or moved may become excessive so that the system becomes overloaded. Ice loads can also cause structural damage. Icing on the recess walls or gates of navigation locks prevents full opening of the gates. Ice formation on the chamber walls prevents full use of the lock width. Ice buildups on dam pier walls can obstruct the movement of the components of dam gates. Ice in any form causes safety hazards for personnel working on or near it. All of these ice problems involve ice formation on or adhesion to critical surfaces at locks and dams. Solutions to these ice problems at navigation projects currently are time-consuming and expensive. This section addresses several approaches to solving the problems of surface ice formation and adhesion.

18-16. Electrical Heating of Lock and Dam Components

Ice adhesion on walls can be prevented by maintaining wall temperatures above 0°C (32°F), or ice collars can be shed periodically by raising the wall temperature intermittently. Possible arrangements include embedded (but removable) electrical heating cables within walls, direct placement of heat mats on walls, and heating dam gate side J-seals.

a. Embedded electrical heaters. The use of embedded electrical heaters that cannot be removed for replacement without major rehabilitation is *not recommended.* Almost every navigation project that has installed embedded electrical heaters has some heaters that have failed and cannot be replaced. The recommendation for those areas where embedded heaters are needed is a replaceable heat tape as described here. During a rehabilitation project, where the concrete walls are to be resurfaced, 1.9-centimeter-diameter (3/4-inch-diameter) stainless steel pipes should be installed, 15 to 20 centimeters (6 to 8 inches) on center, with the bottom ends sealed. At the top of the pier or along the top of the wall, the top ends of the pipes are accessible so that electrical leads can be run from one vertical pipe to the next. The tubes are filled with glycol to act as a heat-transfer fluid, once the self-regulated heat tape is inserted into the pipe. The heat tape can be cut to specific lengths by project personnel and inserted into the pipe. The heat tape is self-regulating and has an output of 121 W/m at 0°C (37 W/ft at 32°F). In the control circuit, timers and thermostats can be added to limit power consumption. If a heat tape fails, then a new length of heat tape may be cut and installed. The cut end should be sealed using heat-shrink tubing, and a cold electrical lead is added to the upper end. Alternate techniques of installing the pipes are by drilling vertical holes along the edge of a pier or wall (however, a major concern is the possibility of the hole breaking out) and by cutting vertical slots 7.5 to 10 centimeters (3 to 4 inches) deep in the wall.

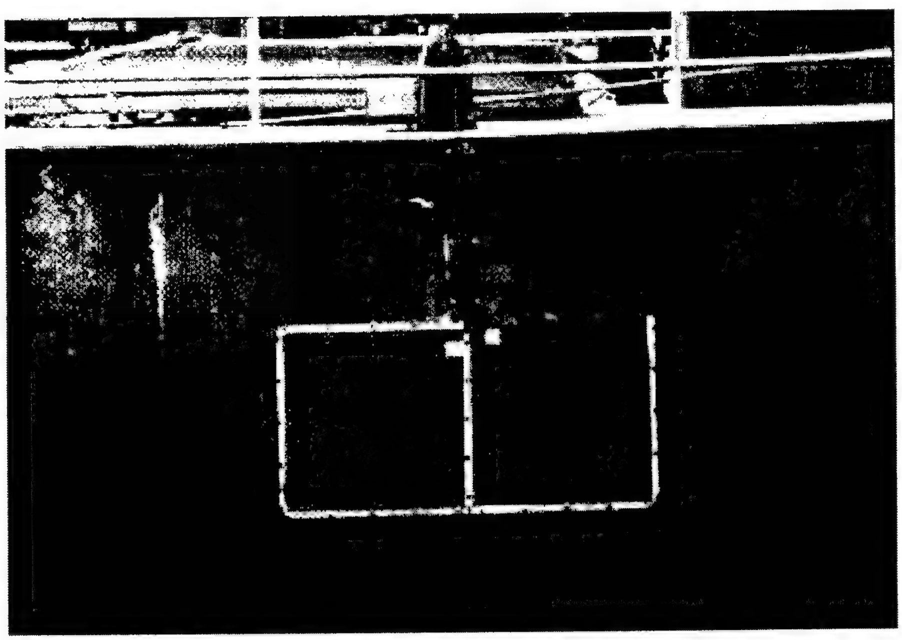
b. Wall heat mats. Fiberglass-reinforced plastic heat mats have been placed directly on a vertical concrete wall at a lock to prevent ice from forming a collar in the gate recess area. The commercially available mats can be provided in any shape or size up to 1.2 × 2.4 meters (4 × 8 feet). Variable power ratings are also available. The mats shown in Figure 18-12 are 1076 W/m^2 (100 W/ft^2). These panels are each 1.2 × 1.2 meters × 0.6 centimeters (4 × 4 feet × 1/4 inch) thick. The mats are very effective in keeping the wall clear of ice. Material costs (1988) for such a mat material were about \$753/m^2 (\$70/ft^2).

c. Heated J-seals on dam gates. Heating the side J-seals improves their ability to reduce leakage past tainter gates, and thus reduce the associated buildup of icing on the walls and the gate structures. This method is easily adaptable at low cost to existing dam gates (using Huntington J-seal Mold No. 3493 or equivalent).

(1) This in situ heating system has been made up so that it can be inserted into the hollow channel of a J-seal; it keeps ice from forming on the seal and increases the flexibility of the seal at lower temperatures. With increased flexibility, the seal better conforms to irregular surfaces, thereby reducing leakage to the downstream side. With little or no leakage, ice formation on the cold, exposed downstream side is substantially reduced. Neither steaming nor "cindering" (i.e., pouring cinders in the water above the locations of the greatest leakages, so that the cinders flow toward the leaks and plug them) were required during tests of the in situ heating system at Starved Rock Lock and Dam on the Illinois Waterway, where it was installed during a recent dam rehabilitation.

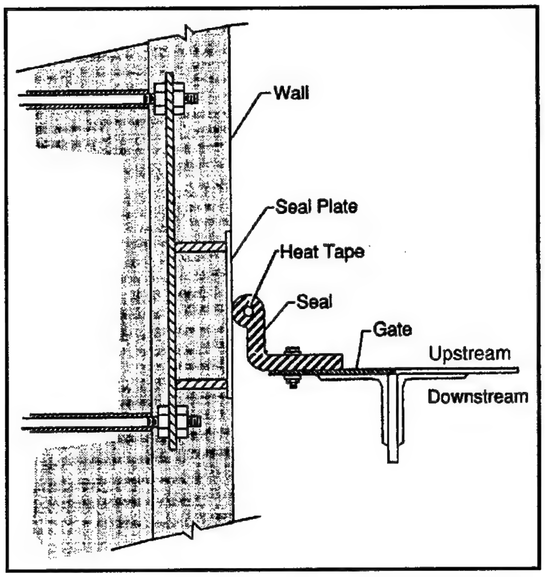
(2) The self-regulating heat trace tape, 208 volts ac at 121 W/m at 0°C (37 W/ft at 32°F), was cut from a spool to a length of 5.5 meters (18 feet). The heat tape was sealed at one end. The other end had a cold electrical lead attached to connect to the electrical power. The J-seal and the inserted heater are shown in Figure 18-13. The 1988 cost of Huntington J-seal Mold No. 3493 was \$45.57/meter

a. General view



b. Detail showing plate over vertical groove in wall above heat mats, which contains electrical leads

Figure 18-12. Fiberglass-reinforced plastic heat mats installed on a miter gate recess wall at Starved Rock Lock on the Illinois Waterway



a. Diagram

b. Heat tape installed in the hollow channel of a J-seal

Figure 18-13. J-seal installation on tainter gate

($14.50/foot). The seal was manufactured as of 1988 by Buckhorn Rubber, 55 W. Techne Center Drive, Milford, Ohio 45150 (800-543-5454). The self-regulating heat trace tape is widely available at an approximate 1988 cost of $16.40/meter ($5/foot). If both seals of a gate are heated and the heaters are operating at maximum power, the operating cost per day is $2.24, assuming 1332 watts at $0.07/ kWhr.

(3) Use of heated J-seals would not preclude the inclusion of embedded electrical heaters in gate pier walls in rehabilitations or new designs, because embedded heaters aid in keeping seal plates ice-free above or below the immediate seal-contact area, so that gates can easily be placed in any chosen position.

18-17. Providing Electricity for Heating to Locks and Dams

Electricity for the heating and deicing of lock and dam components can be supplied by the local electric utility. But since such energy is usually expensive, lower-cost sources of electricity are attractive. Two such alternatives are private hydropower projects installed at Corps navigation projects and, possibly, prepackaged portable hydropower plants.

a. Installed private hydropower. It is the policy of the Corps of Engineers to cooperate with the Federal Energy Regulatory Commission in encouraging private interests to develop hydropower potentials at Corps navigation or flood-control dams. In these cases, the Corps usually has rights to certain portions of the power generated at no cost, as long as it is used for the benefit of navigation. In planning for use of this power, it is recommended that the power needs for ice control be considered and that the total power requirements for navigation be conveyed to parties exploring the feasibility of such private hydropower development.

b. Portable prepackaged hydropower. In those cases where private power development is not present or not likely to be developed, the use of dedicated, portable, packaged hydropower units as

described below (if they are commercially available) should be investigated and compared to purchased power for meeting the needs of ice control at navigation locks and dams.

(1) A study conducted by the University of Iowa during the River Ice Management Program (Nakato et al. 1992) endorsed electrical heating as an attractive method for controlling ice, and suggested consideration of using a then-unconventional means of generating electricity on-site: prefabricated, portable, packaged power plants. The study described a concept in the development and demonstration stage (in 1988) for low-head micro-hydroelectric power plants. These packaged plants were of two sizes: one producing 500 kilowatts at a net head of 5.5 meters (18 feet) and a discharge of 11.3 m^3/s (400 ft^3/s), and the other a 1250-kilowatt unit operating with a 3.7-meter (12-foot) head and 42.5 m^3/s (1500 ft^3/s). These plants gain their portability by being barge-mounted. There is an anchored upstream barge providing the water intake, a siphon penstock, and a downstream barge that carries a submergible horizontal turbine. Trunnion-type joints accommodate variations in upper and lower pool stages. There is no major construction involved for these devices to be installed; they can be placed in a variety of dam configurations, for example, in a gate bay of a navigation dam.

(2) Micro-hydroelectric power-plant output potentials, expressed in combinations of discharge, net head, and resulting power output, are listed in Table 18-1.

Table 18-1
Output Potential of Micro-hydroelectric Power Plants

Discharge m^3/s (ft^3/s)	Power Output (kW) (at 80% efficiency) at Net Heads of:			
	1.5 m (5 ft)	3.0 m (10 ft)	4.6 m (15 ft)	6.1m (20 ft)
7.1 (250)	85	170	255	340
14.2 (500)	170	340	510	680
28.3 (1000)	340	680	1015	1355
42.5 (1500)	510	1015	1525	2035
56.6 (2000)	680	1355	2035	2710

18-18. Mechanical Removal of Ice from Lock Walls

The experimental extension of the navigation season into the winter months on the Great Lakes created ice problems at the Soo Locks. Even under present operating-season schedules, ice poses many problems at the Soo Locks, as well as at many of the lock-and-dam projects on the Ohio River and its tributaries, on the Illinois Waterway, and on the Upper Mississippi River. Ice can adhere to lock walls, building up an ice collar at and below the high pool level, which can interfere with gate opening and closing and interfere with ship passage. For example, ice collars form at the 33.5-meter (110-foot) wide Poe Lock at Sault Ste. Marie, Michigan. Ships of the *Presque Isle* and *Roger Blough* class with their 32.0-meter (105-foot) beams encounter problems when the ice buildup along the walls becomes greater than 0.76 meters (2.5 feet) on each wall. Prior to the development of the ice cutting saw, discussed below, and the copolymer coating (discussed later in paragraph 18-19*a*), a number of methods were used with varying degrees of success to overcome this problem. Steam hoses work well but are extremely slow and require many man-hours. Backhoes have been used to scrape off the ice collar. This is faster then using steam, but still slow. Since the operator cannot see what he is doing he may miss some ice or scrape too deep and damage the lock wall. A high pressure water jet was able to cut off the ice, but the jet was noisy and somewhat dangerous, and the pressure pump was both expensive and difficult to maintain. The selected solution used a high-

flow air screen (discussed in Section I of this chapter), a copolymer coating, and an ice cutting saw. The ice cutting saw is discussed here.

a. Ice cutting saw. CRREL designed and assembled a mechanical cutting system (see Figure 18-14) to remove the ice collars. The unit consisted of two parts: the cutting system, and the drive and propulsion system. The drive and propulsion system was a 48.5-kilowatt (65-horsepower) four-wheel-drive tractor, originally manufactured as a trencher (the tractor could be purchased without the trencher attachment). The drive line for the trencher was modified to accommodate the cutting system by extending the drive shaft and attaching a drive sprocket to its end. While in the cutting mode, the engine powered the shaft and sprocket directly and the drive wheels indirectly through a separate hydraulic drive system, so cutting power and propulsion power could be independently controlled.

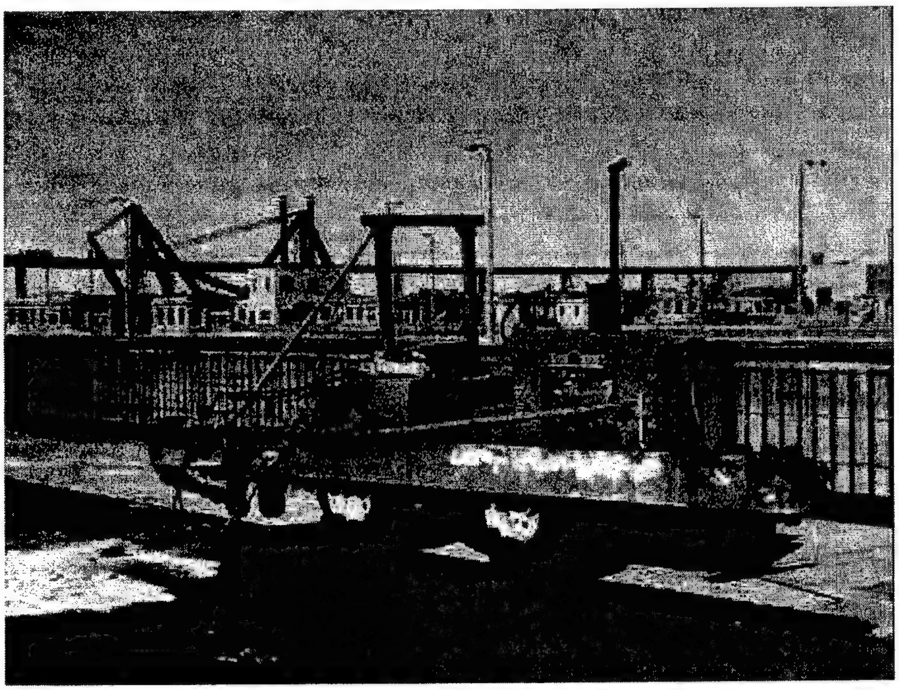


Figure 18-14. Ice cutting saw at Poe Lock

(1) The cutting system was one used in the coal industry—a thin, 8.9-centimeter (3.5-inch) kerf cutter manufactured at the Bowdil Company of Canton, Ohio. It consisted of a rugged bar and chain with cutting bits attached. The bar was 24 centimeters (9.5 inches) wide to the chain guide, 3.8 centimeters (1.5 inches) thick, and 4.85 meters (15.9 feet) long; it was attached to the drive shaft housing. Movement of the bar was hydraulically controlled. Different kerf and bar thicknesses were used, but earlier tests showed that a narrow logging saw was too flexible.

(2) The bar was grooved to accommodate the sprocket drive chain and cutting bits and had a roller nose tip to reduce friction and wear. Chain tension was controlled by a high-pressure hydraulic cylinder capable of exerting 8 kilonewtons (1,800 pounds) at 68.9 megapascals (10,000 psi). The bar and chain hang about 0.76 meters (30 inches) past the side of the tractor and the drive wheels (see Figure 18-15).

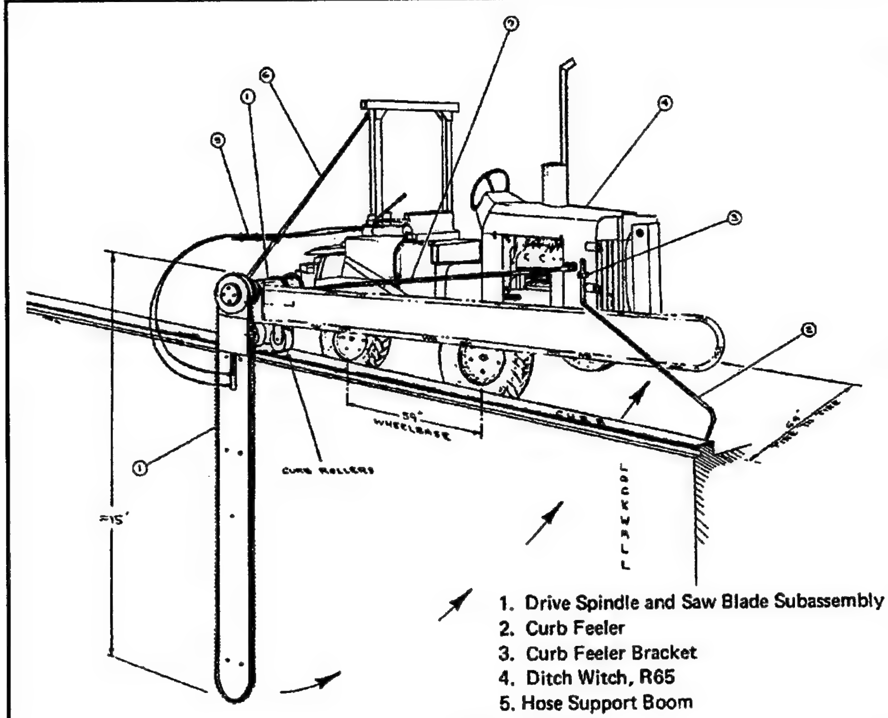


Figure 18-15. Schematic of ice cutting saw

b. Operation of the ice cutting saw. When a problem ice collar built up, the esplanade along the lock wall was cleared of snow. The tractor was then positioned with the right wheels close to the curbing along the wall so that there was about 3.8 centimeters (1.5 inches) of clearance between the wall and the bar and chain. A spacer on the wall side of the bar prevented the cutters from damaging the wall. A guide marker located off the right front wheel was positioned and set so the driver could maintain the proper position by keeping the marker and the reference point (top of curb) aligned. Looked at from the driver's point of view, the chain rotated clockwise with the tension cutting side on top of the bar. To start a slot for the bar, the underside of the saw was used until the tip cut completely through the collar. The slot was cut with the tractor stationary. Once a slot was cut through, the bar was placed in a forward position about 70 degrees from the horizontal. Full throttle operation in third gear produced a chain speed of 1.93 meters per second (380 feet per minute), although chain speeds of up to 2.59 meters per second (510 feet per minute) were possible in fourth gear. A traverse speed of over 0.051 meters per second (10 feet per minute) could be maintained while cutting ice collars 1.8 to 2.4 meters (6 to 8 feet) deep by operating the transmission in third gear at full throttle.

18-19. Surface Treatments to Reduce Ice Adhesion

There is a long history of study in this area for a variety of applications, but surface treatments that shed ice reliably and repeatedly have not yet emerged. The only chemical treatment that has been used successfully on a large scale for truly shedding ice is repeated application of chemicals that depress the freezing point of water. As far as concrete surfaces are concerned, the classic treatment for ice removal is repetitive application of sodium chloride or calcium chloride. Another ice-control method is a permanent or semipermanent chemical coating that reduces the adhesive force between the coated surface and the ice that

forms on it. The ideal material would be one that prevented ice formation entirely. No known coatings do this, but some make the task of ice removal from coated surfaces easier. As an alternative to coatings to reduce ice adhesion, cladding surfaces with materials that shed ice more easily than concrete may be considered.

a. Copolymer coatings. One successful material is a long-chain copolymer compound made up of polycarbonates and polysiloxanes. The most effective coating of the many that have been tested is a solution of polycarbonate–polysiloxane compound, silicone oil, and toluene. The mixture is highly volatile and leaves a thin coat of the copolymer and silicone on the surface to which it is applied.

(1) The copolymer coating was not to be applied to a concrete surface unless it was certain that the concrete behind the coating could resist frost action in a critically saturated condition. Proper application guidance for surface coatings to concrete can be found in *Maintenance and Repair of Concrete and Concrete Structures,* EM 1110-2-2002. The surface to be coated must be clean and dry. For concrete and metal surfaces (bare and painted), steam cleaning is sufficient; however, a detergent may be added to the water of the steam cleaner. This was done, for example, in one case where navigation lock walls were heavily coated with oil and algae. Once the surface is clean and dry, the solution can be sprayed on using an airless spray gun system (Figure 18-16). A single pass will deposit a coat 25 to 51 micrometers (1 to 2 mils) thick. Three coats are recommended for a coating thickness of about 127 micrometers (5 mils). Achieving this final thickness requires about 24.4 liters/100 m^2 (6 gallons/1000 ft^2).

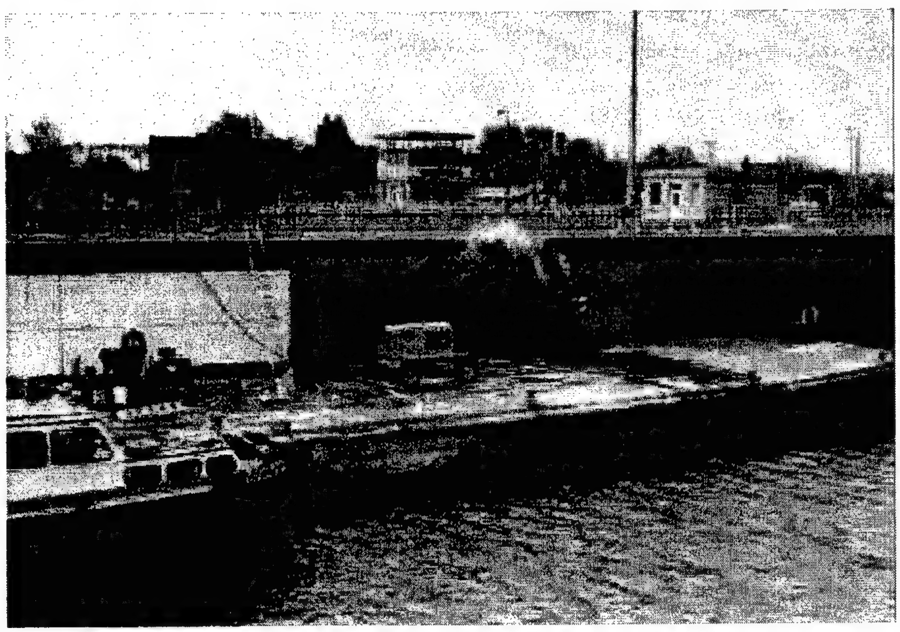


Figure 18-16. Application of copolymer coating

(2) Care has to be taken when mixing the solution. Toluene is a combustible material, so no electrical motor-driven mixer should be used. An air-operated drill motor fitted with a rod with mixer blades has worked satisfactorily. The fumes may also be a health hazard, so that a well-ventilated mixing area should be used. A 208-liter (55-gallon) drum fitted with a bracket to hold the drill motor is a suitable mixing container. Batches of up to 151 liters (40 gallons) can easily be handled. The liquid portions, toluene and silicone oil, are placed in the container first. Then the mixer is started and the copolymer powder is slowly

added. Mixing continues until all solids are dissolved. Then the solution can be transferred to a storage container.

(3) Tests to determine the merits of an undercoating for the copolymer (on concrete surfaces that are worn and rough) show that an epoxy-type coating that acts as a filler over the rough concrete provides a better surface to which the copolymer adheres. Trials of the undercoating and copolymer were done at the Poe Lock, at the St. Marys Falls Canal, at Sault Ste. Marie, Michigan, at Lock No. 4 on the Allegheny River, and at the Starved Rock Lock on the Illinois Waterway. Maintenance and frequency of recoating requirements were monitored. The coating remained in good condition for at least three years.

b. Epoxy coatings. Commercially available two-part epoxy coatings, which can be applied in wet environments, have been tested for ice-phobic characteristics. Several of these coatings perform equally as well as the copolymer coating. They are far more durable since they are an epoxy resin and a polyamine-based curing agent. The epoxy coating gives concrete ideal protection against the ingress of chloride ions, carbon monoxide, and other corrosive agents over the design life. The hard, smooth finish provides a very low friction coefficient, thus reducing the bond strength between ice and substrate.

c. Claddings. Cladding of wall surfaces by materials that shed ice easier than concrete is another approach to solving the problem of ice adhesion. In a demonstration at Starved Rock Lock in Illinois, a 1.2- × 2.4-meter × 1.2-centimeter-thick (4 × 8 foot × 1/2-inch-thick) sheet of high-density polyethylene was fastened to the curved part of the gate recess wall at the quoin end, at the ice-collar level. Hilti studs, 0.5 meters (20 inches) on center, were used for attaching the sheets. Ice formed on the polyethylene surface and the concrete surface equally, but far less effort was needed by lock personnel to manually remove the ice from the plastic material, because of the lower adhesion forces between the polyethylene and the ice. Problems were noted with ice being more difficult to dislodge where the studs protruded, but a redesigned fastening technique could overcome that problem. The polyethylene is not highly durable when pike poles or ice chippers have to be used extensively, though. The use of steam to dislodge the ice collars would eliminate the risk of this damage. The panels are easily and economically replaced, since their 1988 cost was only about $75/m^2 ($7/ft^2).

18-20. References

a. Required publications.
None.

b. Related publications.

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Chapter 19
Operational Solutions

Section I
Vessel Scheduling or Convoying

19-1. Introduction

Frequent vessel passages through ice-covered navigation channels under frigid conditions generate extra ice. In addition, the passage of vessels causes most of the ice grown along tracks opened by previous vessels to be broken into brash ice, which may collect as thick accumulations that eventually impede vessel movements. Field observations, results from ice-tank (laboratory) experiments, and numerical models have shown that navigation tracks opened by transiting vessels become covered with a rather porous layer of brash ice that is approximately 1.5 to 3 times the thickness of the surrounding sheet-ice cover. The greater the number of passages, the thicker the brash-ice layer is likely to become. In addition to hindering vessels, the accumulations of brash ice may form partial or complete ice jams in the navigation channel itself and parallel ridges beneath the ice cover adjacent to the navigation channel. Ice-tank experiments indicate that these ice jams and ice ridges form especially rapidly in shallow river reaches, where they may extend downward to the bottom of the channel. An additional problem that may affect towboats and barges transiting through level or broken ice is their propensity for entrapping and transporting brash ice beneath their flat-bottomed hulls. Ice-tank experiments have shown that the thickness of the ice accumulations on the flat bottoms of towboats and barges increases with decreasing velocity of the vessels, and also increases when lateral confinement (such as provided by ice ridges along the track) does not allow ice pieces to slide off the vessel bottom toward the sides.

19-2. Operational Choices

The problems outlined above suggest two general approaches for their control and mitigation. The first approach entails the use of mechanical methods for controlling brash-ice accumulations at specific channel locations, either by removal or breakup. Icebreakers could be used to loosen and break up such ice accumulations, and to ease transit conditions for commercial vessels, including towboats and barges. However, no icebreakers currently operate on the Ohio and Upper Mississippi Rivers, or on the Illinois Waterway. The second approach involves the optimum scheduling of tow transits and, possibly, the convoying or grouping of tows, which will minimize ice growth in navigation channels.

19-3. Transit Scheduling or Convoying

Results from laboratory experiments and numerical modeling indicate that the basic rule for minimizing the volume of ice grown in a navigation channel is to minimize the total number of transits or tow passages per day. However, the demands of navigation do not generally allow this to be done. Under the assumption that a certain number of transits must take place per day, numerical modeling has shown that varying the time interval between individual transits has no significant effect on the volume of ice grown. But convoying of vessels, i.e., having tows grouped together to transit one after the other, is a special case equivalent to a large, single transit. Under a convoying concept, only one icebreaking event per day would take place. Correspondingly, the total volume of ice produced in a waterway each winter would be minimized.

a. Limitations. Ice-prone waterways may have relatively short periods of severe ice conditions. The river reaches between locks and dams in many locations are relatively short, resulting in frequent lockages of the tows. The vessels may have numerous and varied origins and destinations along the waterways, some of which may lack adequate docking and mooring areas where several tows could be assembled for convoying. Finally, upbound and downbound transits usually have equal frequency. Under these conditions, elaborate transit scheduling, requiring close coordination among the Corps of Engineers, the Coast Guard, and the navigation industry, is unlikely to be administratively or economically feasible.

b. Guidelines for scheduling or convoying tow traffic. For certain river reaches where ice accumulations are particularly severe, or for a given period when cold weather conditions are extreme, partial scheduling or convoying may be chosen as a temporary, expedient measure to help keep the waterway open and to expedite traffic. In such a convoy, normally the leading towboat would be the most powerful one. It is the vessel most likely to be able to do the required icebreaking in the difficult areas. It may also involve the widest tow configuration, thereby opening the navigation channel for the rest of the tows in the convoy. Finally, the most powerful boat may be capable of sustaining a speed sufficiently high to avoid ice accumulations underneath its own barge bottoms, as well as those of the following tows. The size of a convoy may be limited by the time required to pass it through a lock, rather than by the time required to move between two successive locks. While transit scheduling or convoying are not common approaches to alleviating winter transit difficulties in the navigable waterways of the northern United States, they should be considered when extraordinary local and short-term ice conditions are forecast or are at hand.

Section II
Operational Techniques at Locks and Dams

19-4. Introduction

Operational techniques to mitigate ice-related problems at locks and dams tend to be site-specific. Factors influencing the success of any operational technique include the geographical location of the project with respect to river features, the river system that the project is on, the location of the dam in relation to the lock, the presence of an auxiliary lock, the kinds of gates at the lock or dam, the presence or absence of an effective high-flow air system at the lock, the availability of a work boat assigned to the lock, the prevailing wind direction, the amount of winter navigation, and so on. The general problems caused by ice at locks and dams are summarized in Chapter 14: ice obstructing the upper lock approach, fragmented ice floes accumulating in miter gate recesses, ice adhering to lock walls and miter gate recess walls, inoperative floating mooring bitts, vertical check pin (line hook) icing, ice accumulating in the lower lock approach, difficult ice passage at dam spillway gates, ice buildup from spray at dam spillway gates, icing from leakage at gate seals, and ice accumulating on intake screens.

19-5. Physical Ice Removal

Several of the ice problems at locks and dams involve ice adhering to structure surfaces. When methods for the prevention of these ice buildups are not available, it may become necessary to resort to physical removal techniques.

a. Mechanical contact tools for ice removal. Two hand tools that can reliably be used to remove ice from concrete or steel surfaces are the pike pole and the ice chipper. Both of these tools are widely used by lock personnel at sites that experience winter icing problems. Figure 19-1 is a sketch of an ice

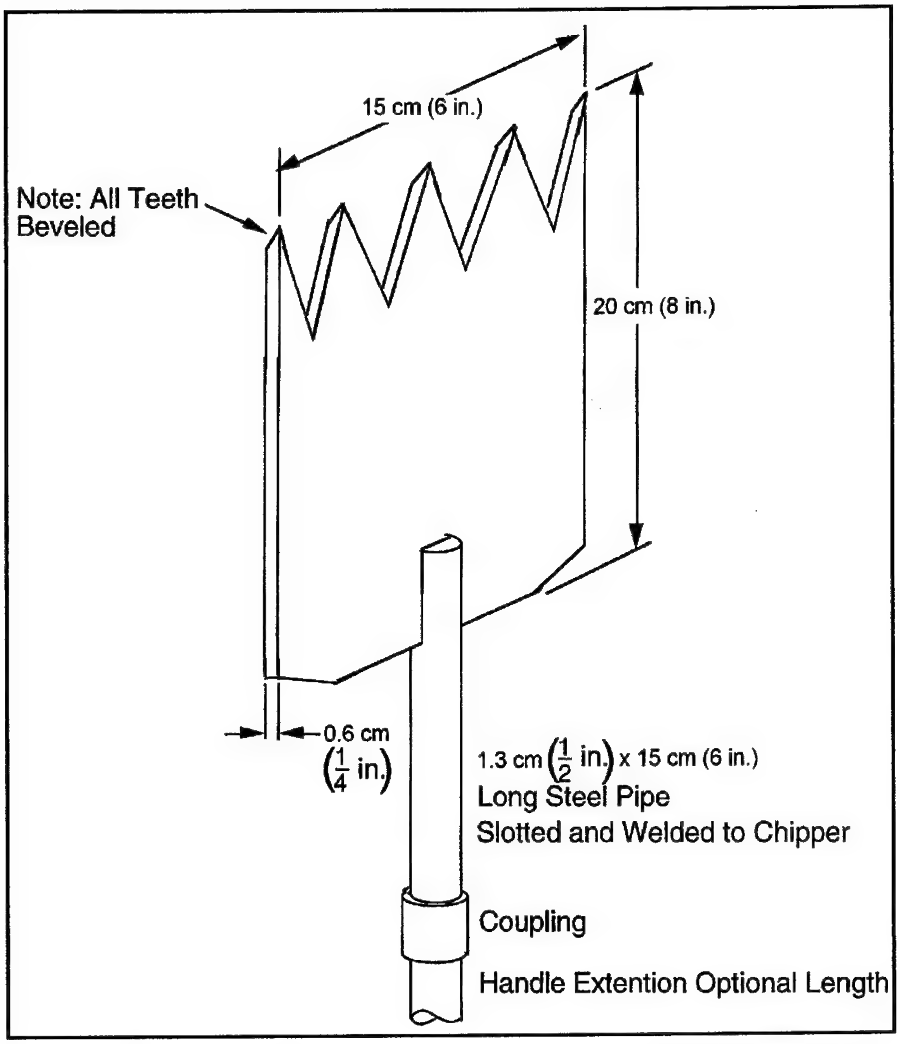


Figure 19-1. Effective design for a manual ice-chipping tool

chipper that has been refined over many years by its users. Large mechanical equipment used to scrape ice collars from lock walls is limited. Backhoes scrape the wall vertically by drawing the bucket teeth up the face of the concrete. With a light machine, this may require more than one pass to scrape through to the concrete, and frequent repositioning of the machine is necessary. With a heavier track-mounted machine, a single pass is usually sufficient. It is easy to move the machine along and there are no spuds to be set. However, with forceful operation, damage to the lock wall is inevitable, and the concrete on grooved or paneled walls could be seriously spalled.

b. Ice removal with noncontact tools. Two techniques for ice removal using noncontacting tools are steam and water jets. Steam, when available at the desired locations, has always been used, often via lances or pipe probes placed and maneuvered by hand. But using steam is slow and time-consuming. The use of high-pressure water jets is rare because of the high horsepower required and the bulkiness of the typical systems. Advances in the design of such systems could make them more attractive.

19-6. Methods Used at Locks

Operational techniques used to mitigate ice problems at locks are briefly listed below. The list of practices can always be enlarged by discussing any particular problem with the lock or maintenance personnel at neighboring project sites.

a. Upper approach. Techniques to reduce upper approach ice problems include using an auxiliary lock with a bulkhead spillway to pass ice, ice lockages in the main chamber or an auxiliary chamber, diagonal high-flow air-screen deflectors, and towboat wheel wash. Other possibilities are the placement of barge traffic awaiting downbound lockage in appropriate configurations to deflect ice, using ice spillways near dams (if present) or using dam gates to pass ice, assuming sufficient flow is available for this purpose.

b. Miter gate recesses. To clear fragmented floes from around miter gates and recesses, towboat wheel wash, miter gate fanning, pike poles and ice rakes, or recess air flushers are used. If the techniques used to deflect floating ice away from the upper approach are effective, then the task of dealing with fragmented ice in the lock chamber and gate recesses will be reduced.

c. Lock walls and recess walls. Ice accumulations or ice collars on lock walls and miter gate recess walls cause width restrictions, as noted earlier. To remove ice collars, or to prevent or reduce the ice growth, various techniques can be considered. If the pool elevation in the chamber is kept high except during lockages, the chamber wall temperature will be near the water temperature. On the other hand, if the pool is kept at a low level, more of the lock wall is exposed to the subfreezing air, allowing the wall to reach temperatures below freezing and thus allowing more ice to form. Removal of the ice is critical in the gate recess area. Common practices at many locks are the labor-intensive ones of using chippers, pike poles, and steam lances. Other techniques that may be available include low-flow bubblers, surface-mounted heat mats, embedded circulation loops of warm fluids, and mechanical tools like backhoes.

d. Mooring bitts. Floating mooring bitts typically freeze in place because of floating ice being pushed into the bitt recess area, as well as because of ice buildup on tracks and related rollers. Currently, personnel at many locks secure the bitts in the top position, not using them during the winter months. This, of course, leaves the bitts unavailable while lock traffic may still be in need of them. The techniques of using a single-point air bubbler or replaceable embedded electric heaters have been developed but are not yet widely adopted. Additional safety systems should be added so that if a floating bitt becomes frozen in the submerged position, it will not be launched skyward when the ice melts.

e. Check pins. Vertical check pins are typically iced over and are forgotten until spring. Lock personnel rely on mooring points on the top of the lock wall to secure the lines during the winter months. Constant monitoring of the lines by deck hands is required. No operational technique appears feasible, other than steaming or chipping the ice on the check pins.

f. Lower approach. The final lock ice problem is the accumulation of ice in the lower approach. Typically, this is not a serious problem for lock personnel. It is possible to stage tows waiting to be locked up in such a manner as to block the encroachment of ice. Water discharge when lowering the lock chamber level helps to clear the immediate lower approach area.

19-7. Methods Used at Dams

Operational techniques used to handle the icing problems associated with dams are much the same as those used at locks. Comments on specific practices at dams are given here. Many dams have been equipped with embedded electrical heaters along gate sealing surfaces. Unfortunately, these heaters have a record of frequent failure, and a new technique has been designed for the installation of a removable heater that is easily exchanged if it becomes inoperative (see paragraph 18-16*a*). Steam lances are commonly used in dam deicing. This is a time-consuming operation but it can be effective. Cindering the dam gate seals (i.e., applying coal cinders to the water above the gate, which then flow toward and plug the gaps at the seals to reduce water leakage) helps to prevent the formation of larger ice deposits on the downstream side of the gate. A new method that has been proposed is a heater inserted in the hollow channel of a J-seal to keep the seal material flexible (see paragraph 18-16*c*). The increased flexibility makes a better seal, eliminating or reducing leakage and ice formation on the downstream side of the gate. The types of gates and their lifting devices are largely site-specific, and techniques used to operate them in winter are developed with time and experience. Typically, submergible gates operated in the submerged position have the fewest operational problems from ice during the winter months. Problems experienced with submergible dam gates are identified in *Submergible Gate Use Within the Corps: Case Histories* (U.S. Army 1985). In many instances, operational techniques now used by lock and dam operators are also described in that report.

Section III
Operational Use of Thermal Resources at Locks and Dams

19-8. Introduction

There is often interest expressed in making beneficial use of energy or thermal resources that may already be present in the vicinity of navigation projects. By this is meant either energy introduced into waterways by man-made sources, or energy that might be extracted from the natural environment (the latter sometimes being called unconventional energy sources).

19-9. Man-Made Energy Sources

Man-made sources of warm water on rivers are often present that either already suppress some ice formation or may be used to cause some ice suppression. The most significant source is the release of cooling water from thermal power plants, which amounts to 150 to 200 percent of the energy produced as electricity. Another source is the release of water from reservoirs that contain slightly warmer water at depth, such that downstream flows may be several degrees above freezing. In addition, there are other less significant sources such as the discharge of treated sewage and warm waste water from industrial processes. While direct application of these thermal energy resources at navigation projects may be difficult, their effects may be helpful in diminishing ice problems in the vicinity of locks and dams. For a complete analysis of the effects on ice covers produced by these thermal energy sources, see Chapter 3, *Ice Control*, paragraphs 3-8 and 3-9.

19-10. Unconventional Energy Sources

Conventional energy sources, such as electricity from public utilities, or the burning of hydrocarbon fuels for heating (either direct heating, or indirect heating such as for generating steam), can be viewed as comparatively expensive sources of energy for ice control at lock and dam installations. Therefore, consideration has sometimes been given to unconventional energy sources, such as sensible heat from

groundwater, heating of a transfer medium by solar energy, or electricity generated from wind energy. A study was conducted during the River Ice Management Program to evaluate the feasibility of using energy from either groundwater, sunlight, or wind to achieve typical ice removal or ice prevention tasks at lock and dam projects (Nakato et al. 1988). In general they found that there is very little promise in pursuing the development of the unconventional energy sources that were examined (groundwater, solar energy, or wind energy). The study concluded that none offered great promise over other more conventional means of ice control at locks and dams.

a. Groundwater heat. Heat energy in groundwater appears to be an attractive energy source. Groundwater is readily available in the vicinity of most rivers. Its temperature is generally near the average annual air temperature for any particular site, meaning that it is well above 0°C (32°F) for nearly all of the inland waterways of the conterminous United States. But the appeal of groundwater is diminished by practical problems involved in extracting and applying its heat, and by the fact that, in the colder areas where heat energy is needed most, the groundwater temperatures are lower. Several approaches for applying the heat contained in groundwater were investigated for preventing or relieving ice buildup on lock components. Both the method of whole-lock heating and the method of heating the water adjacent to the lock walls were ruled out almost immediately as requiring unreasonable amounts of energy. Only the method of circulating warm groundwater through pipes embedded in lock walls to raise the wall temperature was close to being practical. This approach features heating the mass of the walls first, which then lose the heat energy to the air. A significant drawback is that the mass of the walls absorbs so much heat as to make the approach unattractive.

(1) Assume that groundwater at 14°C (57°F) is flowing through an embedded pipe, and the pipe-wall temperature is constant at 0°C (32°F) throughout its length. This simulates the pipe being embedded in a lock wall that is massive compared to the pipe, and in the vicinity of 0°C (32°F) throughout its mass. Two sizes of pipe and two flow amounts for each size were analyzed. Table 19-1 shows how much energy is transferred from the groundwater to the surroundings of the pipe (i.e., the lock wall mass) in a pipe length of 61 meters (200 feet). Also shown is the temperature of the groundwater at the end of the 61-meter (200-foot) run.

Table 19-1
Energy Transferred by Groundwater to Lock Wall

Pipe Size cm (in.)	Flow per Pipe L/s (ft^3/s)	Energy Transferred in 61-m (200-ft) Pipe Run (kW)	Water Temperature at end of 61-m (200-ft) Pipe Run °C (°F)
2.5 (1)	0.63 (0.022)	37	0.1 (32.2)
2.5 (1)	0.95 (0.033)	57	0.2 (32.4)
5.1 (2)	2.52 (0.089)	136	1.2 (34.2)
5.1 (2)	3.79 (0.134)	200	1.4 (34.5)

(2) Note that the values in Table 19-1 are just to keep the pipe-wall temperature at 0°C (32°F). The real case would be to keep the temperature of the lock wall at or above 0°C (32°F); consequently, even larger flows and energy transfers would be needed. Depth of pipe embedment and pipe spacing would be important factors in determining how much larger the flows would have to be. Also, note that if the groundwater was at a lower temperature or moving at lower flow rates, or both, there could be danger of freezing near the end of a 61-meter (200-foot) pipe run. This would indicate the need for shorter pipe-run lengths.

(3) An operational application of embedded pipes would call for several parallel pipes running horizontally at the ice-collar location on the wall, each pipe run having a length of, say, 200 feet, and with the pipes being placed end-to-end with other pipes to cover the entire lock length. The example values above indicate that unless the groundwater temperature is very high, water temperatures decrease toward 0°C (32°F) too quickly (i.e., in too short a distance in the pipes) for this technique to be practical. It appears that other heat sources, such as steam or electric heating, may be more attractive for embedded wall heating systems.

b. Solar energy. In general, the study found that the use of solar energy to assist in keeping lock and dam installations ice-free in winter was not practical. From assumptions based on using standard types of liquid-heating solar collectors, and three values of incoming solar radiation typical of clear-sky daily averages during winter in the Upper Mississippi and Ohio River basins, efficiencies and temperature increases in the heat-transfer liquid were calculated. Efficiency drops markedly as air temperature decreases. In addition, cloudy days, the requirements for storage of heat (to make it available when needed, such as at night), and the capital costs of very large collectors and associated equipment all would combine to discourage extensive consideration of solar energy for lock ice control, in view of the performance levels that can be anticipated.

c. Wind energy. For most locations, normal fluctuations in wind make extraction of its energy unreliable unless some means of energy storage is available. Theoretically, the immediate power output (without storage) from a wind turbine is proportional to the third power of wind speed. Practically speaking, wind turbines often are subject to system controls to minimize the difficulties of extreme variability of power output. In any case, sample calculations illustrated the amounts of power potentially available from wind. For many locations on the inland waterways, an average winter wind speed may be represented by 14.5 km/h (9 mph). A wind turbine having 6.1-meter (20-foot) diameter blades and operating at 50 percent efficiency in this wind condition can generate an average power output of about 0.6 kilowatts, according to commonly used formulas. This means that five or six such wind turbines would be needed to provide power for continuous operation of the comparatively small (3.0 m^2 [32 ft^2]) lock-wall heating panels discussed in paragraph 18-16*b* and shown in Figure 18-12. As with solar energy, the variability of the energy source and the capital costs of the installations and equipment combine to make wind energy use for ice control at locks unattractive.

19-11. References

a. Required publications.
None.

b. Related publications.

Nakato et al. 1992
Nakato, T., R. Ettema, and K. Toda 1992. *Unconventional Energy Sources for Ice Control at Lock and Dam Installations*, Special Report 92-13, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

U.S. Army 1985
U.S. Army 1985. "Submergible Gate Use Within the Corps: Case Histories," Report to U.S. Army Cold Regions Research and Engineering Laboratory, June 1985; prepared by U.S. Army Corps of Engineers, Louisville (Kentucky) District.

Appendix A
Glossary

Agglomerate	An ice cover floe formed by the freezing together of various forms of ice.
Anchor ice	Submerged ice attached or anchored to the bottom, irrespective of the nature of its formation.
Anchor ice dam	An accumulation of anchor ice that acts as a dam and raises the water level.
Beginning of breakup	Rivers: Date of definite breaking or movement of ice attributable to melting, currents, or rise of water level. Lakes: Date of visual evidence of initial deterioration along shoreline, such as the appearance of shore leads.
Beginning of freezeup	Date on which ice forms a stable winter ice cover.
Black ice	Transparent ice formed in rivers and lakes.
Border ice	Ice sheet in the form of a long border attached to the bank or shore; *shore ice.*
Brackish ice	Ice formed from brackish water.
Brash ice	Accumulations of floating ice made up of fragments not more than about 2 meters (6 feet) across; the wreckage of other forms of ice.
Breakup	Disintegration of ice cover.
Breakup date	Date on which a body of water is first observed to be entirely clear of ice and remains clear thereafter.
Breakup jam	Ice jam that occurs as a result of the accumulation of broken ice pieces.
Breakup period	Period of disintegration of an ice cover.
Candle ice	Rotten columnar-grained ice.
Channel lead	Elongated opening in the ice cover caused by a water current.
Channelization	Modification of a natural river channel; may include deepening, widening, or straightening.
Columnar ice	Ice consisting of columnar-shaped grains. The ordinary black ice is usually columnar-grained.

Concentration	The ratio (in eighths or tenths) of the water surface actually covered by ice to the total area of surface, both ice-covered and ice-free, at a specific location or over a defined area.
Conveyance	A measure of the carrying capacity of a river channel.
CRREL	U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.
Degree-day	Also termed *freezing degree-day*, a measure of the departure of the mean daily temperature *below* a given standard, usually 0°C (32°F). For example, a day with an average temperature of –5°C (23°F) represents 9 freezing degree-days by the Fahrenheit scale (5 freezing degree-days by the Celsius scale). Accumulated freezing degree-days (AFDD) are simply the sum of any number of degree-days. For example, the AFDD of a week with mean daily temperature of –5, 0, +5, 0, –5, –10, and –5°C are 20 freezing degree-days by the Celsius scale (23, 32, 41, 32, 23, 14, and 23°F) 36 freezing degree-days by the Fahrenheit scale.
Drifting ice	Pieces of floating ice moving under the action of wind or currents.
Dry crack	Crack visible at the surface but not extending through the ice cover, and therefore dry.
Duration of ice cover	The time from freezeup to breakup of an ice cover.
Dynamic ice pressure	Pressure attributable to a moving ice cover or drifting ice. Pressure occurring at moment of first contact termed ice impact pressure.
Floating ice	Any form of ice floating in water.
Floc	A cluster of frazil particles.
Floe	See *Ice floe*.
Flooded ice	Ice that has been flooded by melt water or river water and is heavily loaded by water and wet snow.
Floodplain	Land area adjoining a water body that is not normally submerged but may be submerged during flood conditions.
Fracture	Any break or rupture formed in an ice cover or floe by deformation.
Fracture zone	An area that has a great number of fractures.
Fracturing	Deformation process where fracture occurs and the ice is permanently deformed.
Frazil	Fine spicules, plates, or discoids of ice suspended in water. In rivers and lakes it is formed in supercooled, turbulent waters.

Frazil slush	An agglomerate of loosely packed frazil that floats or accumulates under the ice cover.
Freezeup date	The date on which the water body is first observed to be completely frozen over.
Freezeup jam	Ice jam formed as frazil ice accumulates and thickens.
Freezeup period	Period of initial formation of an ice cover.
Frost smoke	Fog-like clouds caused by contact of cold air with relatively warm water that can appear over openings in the ice or leeward of the ice edge and may persist while ice is forming.
Froude number	$F_R = V\sqrt{gH}$ where V = mean velocity, g = gravitational acceleration, and H = water depth.
Frozen frazil slush	Accumulation of slush that has completely frozen.
Glare ice	Ice cover with a highly reflective surface.
Gorge	An archaic or localized term for an ice jam; see *ice gorge.*
Grounded ice	Ice that has run aground or is in contact with ground underneath it.
Hanging dam	A mass of ice composed mainly of frazil or broken ice deposited under an ice cover in a region of low flow velocity.
Hinge crack	Crack caused by significant changes in water level.
Hummock	A hillock of fractured ice that has been forced upward by pressure.
Hummocked ice	Ice piled haphazardly, one piece over another, to form an uneven surface.
Hummocking	The pressure process by which ice is forced into hummocks.
Hydraulic radius	$R = A/p$, where A = cross-sectional flow area, p = wetted perimeter.
Ice arch	Frazil or fragmented ice that has stopped moving and bridges across a river channel; also called an *ice bridge.*
Ice boom	Floating structure designed to retain ice.
Ice bridge	A continuous ice cover of limited size extending from shore to shore like a bridge.
Ice cover	A significant expanse of ice of any form on the surface of a body of water.
Ice crossing	Man-made ice bridge.

Ice floe	Free-floating piece of ice greater than about 1 meter (3 feet) in extent.
Ice foot	A narrow fringe of thickened ice attached to the shore and unmoved by changes in water level.
Ice free	No floating ice present.
Ice gorge	A local term for ice jams, used primarily on the central U.S. rivers. This term is subject to regional variations in meaning.
Ice jam	A stationary accumulation of fragmented ice or frazil, which restricts or blocks a stream channel. This term is subject to regional variations in meaning.
Ice jamming	Process of ice accumulation to form an ice jam.
Ice ledge	Narrow fringe of ice that remains along the shores of a river after breakup. Also termed *shear wall.*
Ice push	Compression of an ice cover, particularly at the front of a moving section of ice cover.
Ice run	Flow of ice in a river. An ice run may be light or heavy, and may consist of frazil, anchor, slush, or sheet ice.
Ice sheet	A smooth, continuous ice cover.
Ice shove	On-shore ice push caused by wind and currents, changes in temperature, etc.
Ice twitch	Downstream movement of a small section of an ice cover. Ice twitches occur suddenly and often appear successively.
In situ breakup	Melting in place.
Lake ice	Ice formed on a lake, regardless of observed location.
Lead	Long, narrow opening in the ice.
Manning equation	$V = 1.486\ R^{2/3}S^{1/2}/n$ in English units ($V = R^{2/3}S^{1/2}/n$ in SI units) where V = mean flow velocity, R = hydraulic radius, and S = hydraulic slope; n is a coefficient of roughness.
Mush ice	Floating accumulation of very fine ice fragments (around 0.25 centimeters [0.1 inch] in size) that is somewhat cohesive.
New ice	A general term for recently formed ice, which includes frazil ice, slush, shuga (sludge), and other types of ice.
Overbank flow	Flow that exceeds the level of a river's banks and extends into the floodplain.

Pancake ice	Circular flat pieces of ice with raised rims; the shape and rim are caused by repeated collisions.
Polynya	Any nonlinear-shaped opening enclosed by ice. Polynyas may contain brash ice or be covered with new ice.
Pressure ridge	Line or wall of broken ice forced up by pressure.
Puddle	Accumulation of melt water on ice, mainly from melting snow but in the more advanced stages also from the melting of ice. Initial stage consists of patches of melted snow.
Rafted ice	Type of deformed ice formed by one piece of ice overriding another.
Rafting	Pressure processes whereby one piece of ice overrides another. Most common in new ice.
Ridge	A line or wall of broken ice forced up by pressure. May be fresh or weathered.
Ridged ice	Ice piled haphazardly, one piece over another in the form of ridges or walls.
Riprap	Rocks strategically placed against riverbanks or beds to prevent erosion of underlying material.
Rotten ice	Ice in an advanced stage of disintegration.
Rough ice	General term for ice covers with rough surfaces.
Sea ice	Any form of ice originating from the freezing of seawater.
Shear crack	Crack formed by movement parallel to the surface of the crack.
Shear wall	Ice accumulation having a vertical wall or face and remaining along the shores of a river after an ice jam has released. The height of the vertical face provides an estimate of the thickness of the ice jam.
Shearing	Motion of an ice cover because of horizontal shear stresses.
Sheet ice	A smooth, continuous ice cover formed by in situ freezing (lake ice) or by the arrest and juxtaposition of ice floes in a single layer.
Shore depression	Depression in the ice cover along the shore often caused by a change in water level.
Shore ice	See *border ice*.
Shore lead	A water opening along the shore.
Skim ice	Initial thin layer of ice on a water surface.

Sludge	An accumulation of spongy ice lumps formed from compressed frazil, slush, snow slush, or anchor ice.
Slush ball	Result of extremely compact accretion of snow, frazil, and ice particles. This is produced by wind and wave action along the shore of lakes or in long stretches of turbulent flow in rivers.
Slush-ice run	Ice run composed mainly of slush ice.
Snow ice	Ice that forms when snow slush freezes on an ice cover. The presence of air bubbles makes it appear white.
Snow slush	Snow that is saturated with water on ice surfaces, or as a viscous mass floating in water after a heavy snowfall.
Static ice pressure	Pressure developed by a static ice cover.
Stranded ice	Ice that has been floating and has been deposited on the shore by a lowering of the water level.
Supercooled water	Water whose temperature is slightly below the freezing point (0°C or 32°F).
Surface crack	Crack visible at the surface.
Thalweg	Deepest portion of the river channel; the line of major flow.
Thaw holes	Vertical holes in ice formed when surface puddles melt through to the underlying water.
Thermal crack	Crack caused by contraction of ice caused by a change in temperature.
Through crack	Crack extending through the ice cover. Sometimes called a wet crack.
Tide crack	Crack caused by rise and fall of tides. A special kind of hinge crack.
Unconsolidated ice cover	Loose mass of floating ice.
Water slope	Change in water surface elevation per unit distance.
Water stage	The water surface elevation above the bottom of the river channel or above some arbitrary datum.
Weir	Barrier placed in a river to raise water elevation.
White ice	See *snow ice.*

Appendix B
Ice Jam Mitigation Case Studies

B-1. Kankakee River, Illinois—Thermal Control

a. The upstream end of the backwater from the Dresden Island Lock and Dam on the Illinois River extends to about River Mile 3.5 on the Kankakee River near Wilmington, Illinois. Frazil ice floes form a stable ice cover on the pool, which thickens as frazil ice then deposits beneath the ice cover. The thick frazil ice deposit requires more force to break up than the thinner upstream ice and provides an obstruction to the passage of upstream river ice, which breaks up prior to this thick ice deposit. An ice jam often forms at the upper end of the deposit and progresses upstream, flooding the city of Wilmington and surrounding areas. The ice jam flood in 1982, which caused more than $8 million in damages, was followed by other ice jam events in 1984 ($500,000) and 1985 ($1 million). Several alternative ice jam mitigation measures were considered. Because of the proximity of the cooling pond for the Dresden nuclear power plant, thermal ice control appeared feasible. The intent of the thermal control was to thin or melt the thick frazil deposits that resist breakup, thus allowing the fragmented ice from upstream to pass unobstructed.

b. In a demonstration project, 20°C (68°F) water from the cooling ponds adjacent to the Kankakee River near Wilmington was siphoned in three 0.76-m-diameter (30-inch-diameter) pipes into the river upstream of the ice cover for 2 weeks prior to the anticipated breakup in 1988 (Figure B-1). The maximum siphon flow is 4.25 m^3/s (150 ft^3/s) compared with the expected river flow of approximately 113 m^3/s (4000 ft^3/s). The measured rise in water temperature was less than 0.56°C (1°F). The warm water input melted the existing ice so that ice floes passed unhindered during the natural breakup period and flooding was averted (Figure B-2).

c. This $450,000 system worked successfully for 2 consecutive years. There were no reported negative environmental impacts.

B-2. Hardwick, Vermont—Improved Natural Storage, Ice Retention, Mechanical Removal

a. Relatively frequent breakup ice jams have caused serious damage in this small Vermont town. A combination of techniques is used to reduce flooding impacts.

b. To slow the movement of broken ice, two booms were constructed (Figure B-3). The vertically oriented tire booms, which are suspended from shore, collect broken ice during breakup, some of which is stored on the overbanks. The booms delay the downstream passage of ice while ice removal is performed in town. Since the winter of 1983–84, these booms have been placed upstream from town annually. Although the booms occasionally fail, they do provide ice retention.

c. An ice storage area downstream of the town accommodates some of the ice that jams and thereby provides added protection. In addition, when local officials first begin to notice serious ice jams developing, the town road crew mechanically breaks up and removes the ice to keep the river open.

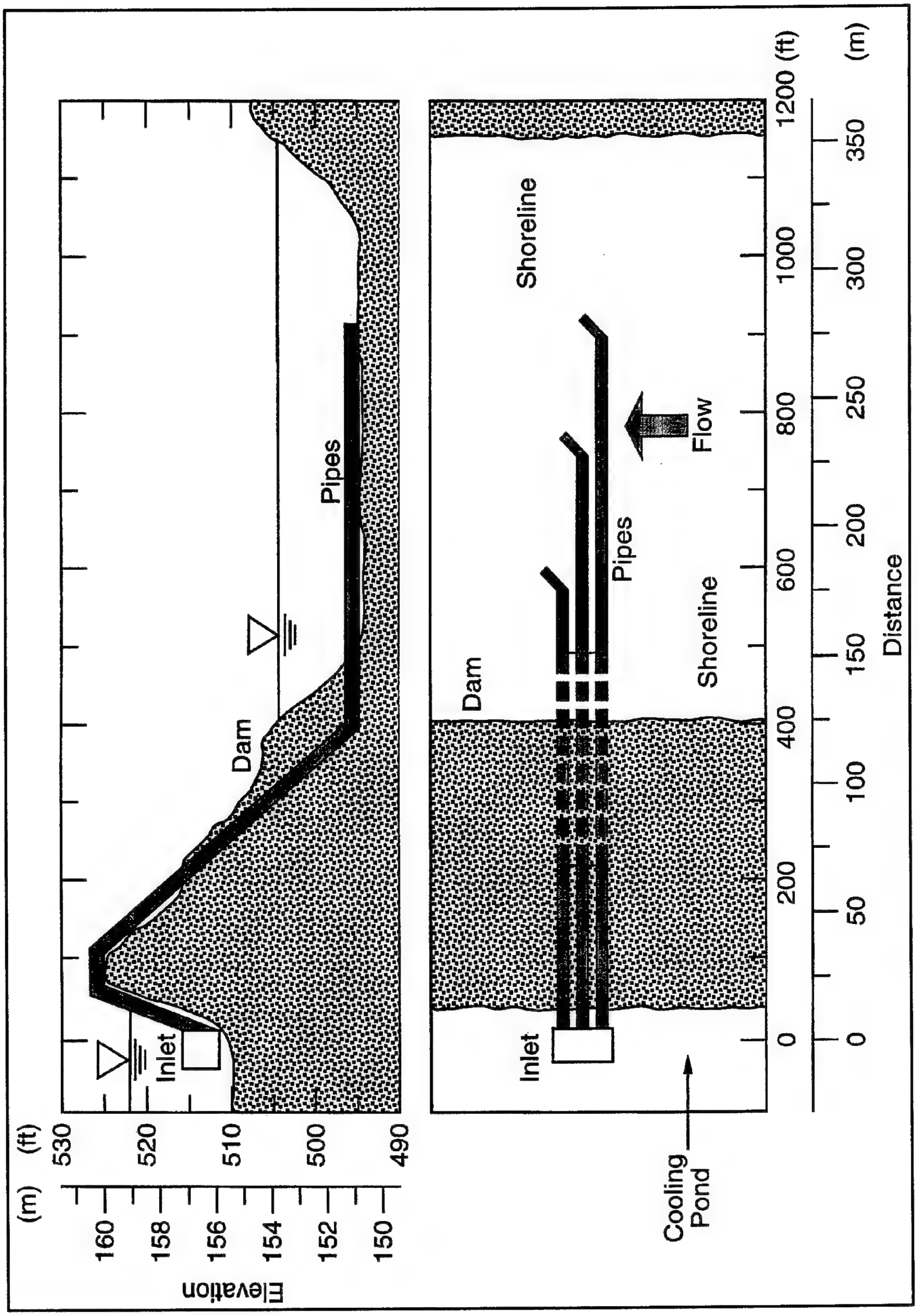


Figure B-1. Schematic of siphon system, Kankakee River, Illinois

Figure B-2. Map of meltout, Kankakee River, Illinois

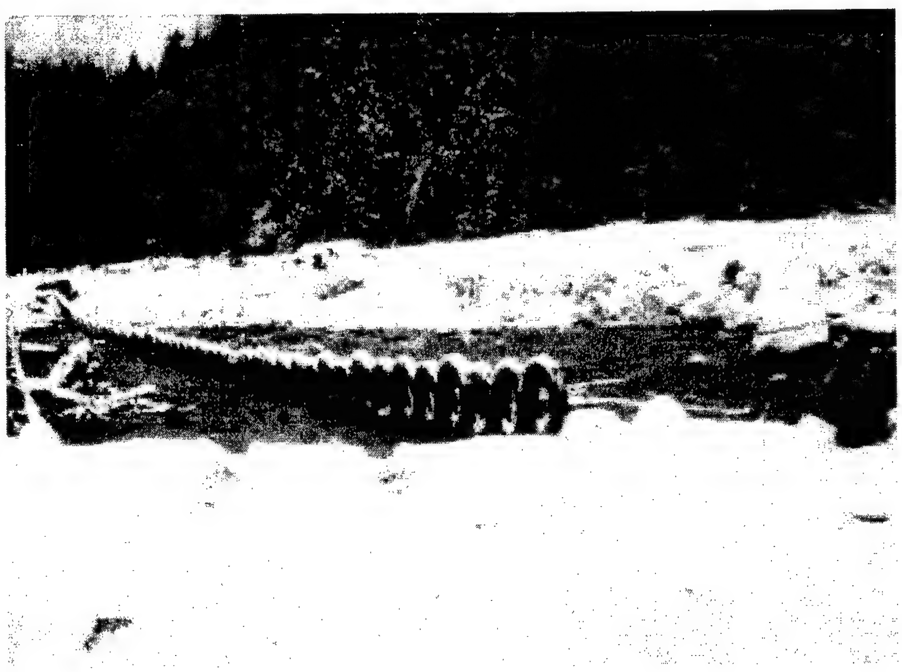


Figure B-3. Tire boom at Hardwick, Vermont

B-3. Oil City, Pennsylvania—Floating Ice Boom, Revised Operational Procedures, Ice Control Dam

a. Oil City is located in northwestern Pennsylvania. The city suffered chronic ice jam flooding from the mid-1880s to the mid-1980s. In February 1982, ice jam flooding caused more than $4 million in damages in downtown Oil City.

b. Research indicates that the ice jam flooding was caused in part by a massive deposit of frazil ice naturally occurring in a long, deep pool in the Allegheny River downstream of Oil City and extending upstream past the confluence with Oil Creek. Large quantities of frazil generated in the creek were also deposited in the river and backwater at the mouth of the creek. The ice on Oil Creek typically broke up and moved downstream before the ice cover on the Allegheny River. The tributary ice ran unimpeded to the river until it met the stable ice at the confluence with the Allegheny River and formed an ice jam.

c. An environmentally and economically beneficial floating structure (Figure B-4) was designed and installed upstream of the city on the Allegheny River to quickly form a stable ice cover to suppress further frazil generation and minimize excessive deposition in the trouble area. Discharge at an upstream dam was decreased during freezeup to allow the rapid formation of a stable ice cover at the boom. The floating boom was installed during the 1982–83 winter at a cost of $900,000. Since its installation, the boom has been fully effective and the river has remained relatively ice-free downstream from the boom in spite of extremely cold winters (Deck 1984).

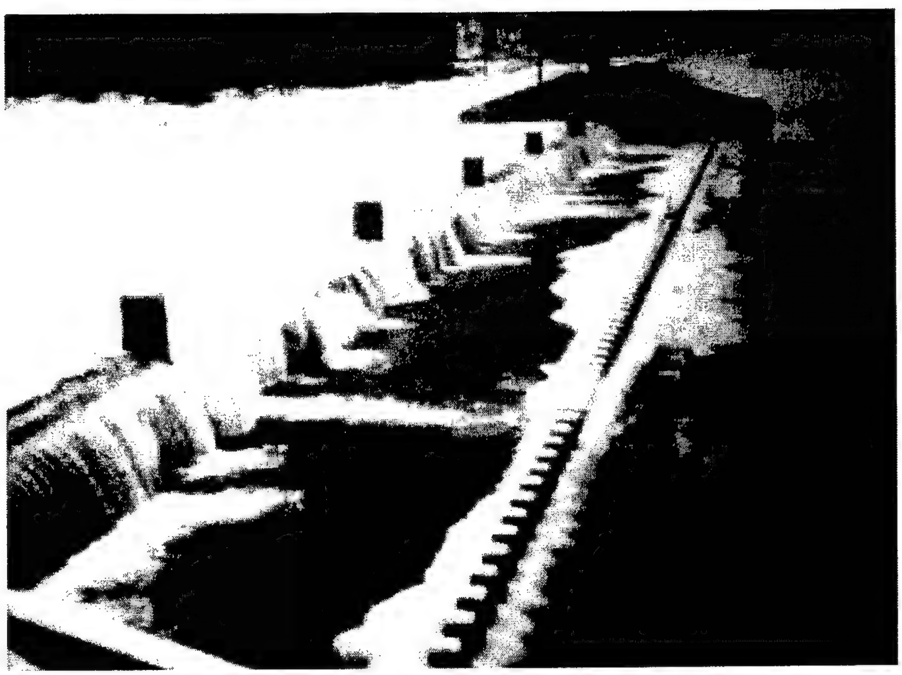


Figure B-4. Oil Creek ice-control structure, Oil City, Pennsylvania

d. A permanent ice-control structure was also constructed on Oil Creek by the Pittsburgh District of the Corps of Engineers in 1989. The structure is 1.5 meters (5 feet high), 107 meters (351 feet) long, and includes a 13.7-meter-wide (45-foot-wide) leaf gate, which allows for sediment and fish passage, as well as recreational use by canoeists and fishermen. Two low-flow pipes also provide fish passage. Levees were

constructed on both upstream banks to contain the Standard Project Flood. The project cost was $2.2 million (Wuebben and Gagnon 1995). No damaging ice jam has occurred in Oil City since the Allegheny River ice boom and Oil Creek ice control structure were put into use.

B-4. Lancaster, New Hampshire—Weir, Ice Retention, Storage

a. Lancaster, New Hampshire, experienced ice jams every year because of the breakup of the ice cover on the Israel River. Broken ice passage is impeded by a natural frazil deposit that forms at the change in slope, which occurs at the upper end of the backwater formed by the confluence with the Connecticut River. Few ice jams were reported prior to 1936, probably because four dams then in existence decreased frazil production, provided frazil ice storage, decreased the downstream transport of frazil ice, and delayed the downstream passage of broken ice. The dams have been removed since that time.

b. The Corps' New England Division (now New England District) and CRREL designed and built an ice control project to reduce the production and transport of frazil ice and decrease the volume of ice available to ice jams downstream. Environmental and financial constraints limited the scope of the project, which ideally would have provided the same protection as the four dams. The project consists of two parts: 1) a submarine net to capture surface ice, and 2) a 36.6-meter-long by 2.7-meter-high (120-foot-long) by 9-foot-high permanent weir located several miles downstream (Figure B-5). The submarine net is a form of suspended ice retention structure that allows water to flow through but captures floating ice pieces, which are then stored in overbank floodplains.

c. The ice control weir includes four 1.2-meter-wide by 2.4-meter-deep (4-foot-wide by 8-foot-deep) sluiceways for fish passage. During the winter, stop logs or metal bar racks are placed in the sluiceways to develop an ice retention pool. The pool forms an ice cover, and frazil ice generated upstream deposits beneath the ice cover. After the ice cover has formed, two of the gates are opened, allowing the pool level to drop. This creates additional water storage in the pool area, provides additional discharge capacity through the weir, and slightly delays the breakup and movement of ice through the pool as well. The project, which cost $300,000 was completed in 1982. Although costs constrained the size of the project to less than ideal, no major flooding has occurred since this relatively inexpensive, innovative project was constructed (Axelson 1991).

B-5. Idaho Falls, Idaho—Land Acquisition

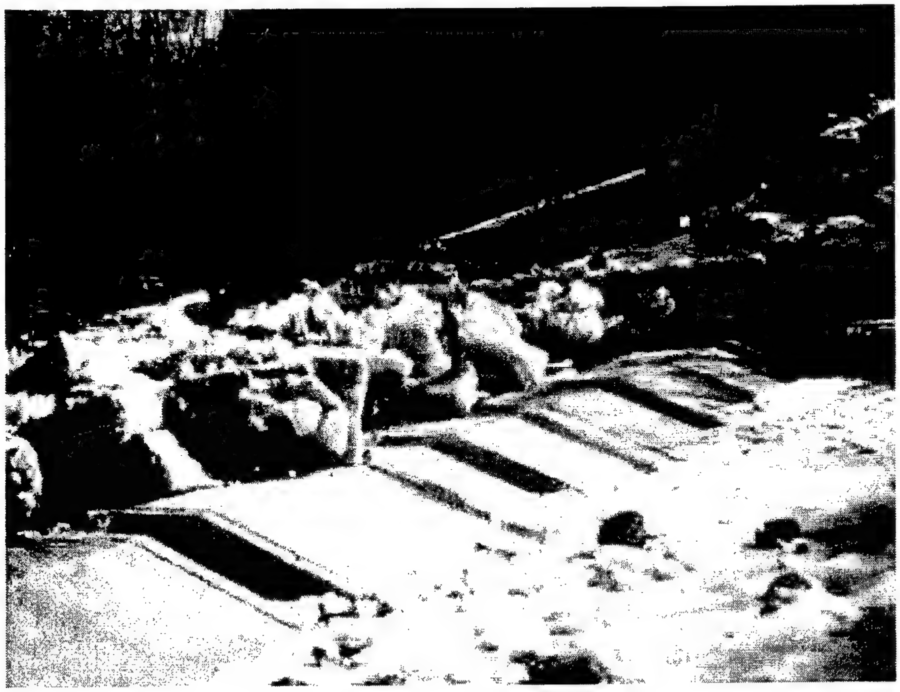
In 1982, two hydroelectric dams were removed and rebuilt on the Snake River near Idaho Falls, Idaho. Freezeup ice jam floods on the Snake River affected Bear Island homeowners during the winters of 1982–83 and 1984–85. Ice jam floods also threatened two houses on the west bank of the river. The homeowners associated their flooding problems with the rebuilt dams located 9.7 kilometers (6 miles) downstream. As a result, they requested help from the city of Idaho Falls, the Federal Energy Regulatory Commission, and elected officials. Field data collection and hydraulic analyses indicated that ice jams were caused by frazil produced in turbulent open-water sections of the Snake River. The results showed that the changes in reservoir levels and the dams had no direct effect on ice jam flood levels in one area, although two properties were affected by changes in reservoir levels. Based on CRREL's recommendations, the City of Idaho Falls decided to purchase the two properties affected by the Upper Power Project (Zufelt et al. 1990).

a. Installing racks in sluiceways

Figure B-5. Lancaster, New Hampshire, weir

B-6. Platte River, Nebraska—Dusting

a. In February 1978, disastrous ice jam flooding took place on the Platte River in Nebraska, causing millions of dollars in damages. Record cold in January 1979 produced both extremely thick ice on the Platte River and its tributaries and a consequent threat of similar ice jams during spring breakup. Ice dusting, approximately 3 weeks before breakup, was recommended for alleviating ice jam floods.



b. Ice accumulated behind structure in early spring

Figure B-5. (Concluded)

b. The Nebraska Civil Defense Agency decided to try dusting selected areas with technical assistance from the Corps. The Corps assisted with advance preparation for the ice dusting operation, during the actual dusting procedures to ensure a proper application rate on the test areas, and during subsequent measurements to evaluate the effectiveness of the program. Dusting was performed using coal ash and slag from a local power plant.

c. Two periods of breakup occurred in March 1979. Because the dusted ice had already started to deteriorate, the jams were minor, even following heavy rains. The ice and water flowed smoothly down the channel with no flood damages (U.S. Army 1979).

d. Similar dusting operations were repeated in March 1994, prompted by severe ice jam flooding in the spring of 1993 that threatened the water wells supplying the city of Lincoln, Nebraska (U.S. Army 1994).

B-7. Allagash, Maine—Floodproofing, Relocation

a. Rainfall and 5 to 6 days of mild weather resulted in breakup ice jams and severe flooding on the St. John, Little Black, Allagash, and Aroostook rivers of northern Maine in April 1991. In Allagash, two bridges and 11 homes on the St. John River were destroyed; 22 other homes suffered damages. A 30-meter (1000-foot) section of a state highway was washed away. Ice jam flooding also caused evacuations and damage to 16 homes in neighboring towns. Damages totaled more than $14 million, mostly for rebuilding bridges, roads, and other public works (Federal Emergency Management Agency 1991).

b. Raising the affected buildings was considered. However, it was determined that elevation of the ground floor of homes to meet the requirements of the National Flood Insurance Program and local floodplain regulations might not provide adequate protection from future ice jams. In the town of Dickey, several residents indicated a willingness to relocate outside the floodplain. The following permanent settlement changes were made:

Three new homes were built at higher elevations on the original lots, and one home was repaired and moved to higher ground on the same lot.

Two new homes were constructed on new sites outside the floodplain, three homes were repaired and were moved to higher ground outside the floodplain, and two destroyed homes were replaced with mobile homes on higher sites.

Thirteen wells or septic systems were replaced with mitigation measures, meaning they were floodproofed or moved to higher ground.

B-8. References

a. Required publications.
None.

b. Related publications.

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Appendix C
Typical River Ice Management Study

C-1. General

A River Ice Management Study is conducted for the purpose of developing a River Ice Management Plan for a particular river or river basin. Typically, the River Ice Management Study would identify several options and develop schedules of time and costs for each. Then the chosen option or combination of options would go into the recommended River Ice Management Plan, which would become an operating document at the District level. The typical River Ice Management Study would be composed of the following elements.

C-2. Elements

a. Inventory of river characteristics.

- River reaches delineated and evaluated.
- Major tributaries evaluated.
- Hydraulic and flood control structures identified (including features and operational characteristics).
- Hydraulic and hydrologic data.

b. Description of ice problems.

- Ice and winter histories.
- Winter navigation and traffic characteristics.
- Project operational techniques in winter (site-specific).
- Ice problem identification and description (site-specific).
- Current ice problem mitigation techniques.

c. Ice–hydraulic–meteorological data.

- Existing data summarized (including stations, data types, collection, and processing).
- Data gaps identified.
- Recommendations for additional data collection (site-specific).
- Ice forecasting system (including capabilities, function, operation, and integration with existing hydraulic models).

d. Communications systems.

- Existing ice information reporting systems.
- Recommendations for improvements (including content, frequency, availability, and dissemination of current ice information).

e. Possible structural solutions.

- Techniques available.
- Application of site-specific structural solutions.

- Determination if Environmental Impact Statement is needed.

f. Possible operational solutions.

- Techniques available.
- Application of site-specific operational solutions.

g. Recommended Functional River Ice Management Plan for Subject River or Basin.

- Data collection program.
- Development and integration of ice forecasting methodology.
- Recommended structural ice control measures.
- Recommended operational techniques.
- Operational guide.
- Ice emergency options (including decision "tree" or "matrix" for determining when to close the river to navigation because of extreme ice conditions).
- Implementation plan.
- Schedule of structural improvement costs and annual operating costs.
- Benefit–Cost Analysis for structural measures (done by District even if River Ice Management Study is conducted by non-District entities).